

STANDARDS DEVELOPMENT BRANCH OUIDE



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SOURCE SAMPLING OF
"ACE " MODEL 2165-D
GRAIN DRYER EQUIPPED
WITH BEHLEN "ROTOVAC"
POLLUTION CONTROLS

ARB-TDA Report No. 60 -80A

February 1980



Ministry
of the
Environment

The Honourable
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Minister

Graham W. S. Scott, Q.C.,
Deputy Minister

17400

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17400 Source Sampling of

"ACE" Model 2165-D Grain Dryer
Equipped with Behlen "Rotovac"
Pollution Controls

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SOURCE SAMPLING
OF
"ACE" MODEL 2165-D GRAIN DRYER
EQUIPPED WITH
BEHLEN "ROTOVAC" POLLUTION CONTROLS

ARB-TDA- Report No. 60-80A

for

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February 1980

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ABSTRACT

The results of the approved compliance test, conducted in accordance with procedures established with the Ontario Ministry of the Environment on an "ACE" Model 2165-D grain dryer equipped with Behlen "Rotovac" particulate emission controls are summarized below:

Total "Rotovac" Emission Rate	$1.81 \pm 0.03 \text{ lb}_m/\text{hr}$
Uncontrolled Emission Rate	$101 \text{ lb}_m/\text{hr}$
Emission Factors with Control	$2.68 \pm 0.13 \text{ lb}_m/1000 \text{ bu dried corn}$ $0.271 \pm 0.016 \text{ lb}_m/1000 \text{ lb}_m \text{H}_2\text{O removed}$
Emission Factor Without Control	$148 \text{ lb}_m/1000 \text{ bu dried corn}$
Overall Energy Efficiency	$62 \pm 4\%$
Thermodynamic Drying Efficiency	$63 \pm 3\%$

It is recommended that a more comprehensive energy utilization study be conducted to help minimize fuel consumption since it represents more than 95% of grain drying energy costs.

ACKNOWLEDGEMENTS

The authors are indebted to the members of the Source Sampling Working Committee Grain Dryer Task Force and the Technical Committee of the Ontario Grain and Feed Dealers for their interest and technical advice during this study.

Special thanks are extended to Messrs. W. P. Suboch, V. Ozvacic, J. F. McDonald and J. T. Manuel for their ready willingness to discuss problems of mutual interest.

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I. BACKGROUND

This report outlines the findings of the testing program carried out under the terms of Purchase Order A61956 issued by the Ontario Ministry of the Environment on 8 November 1979.

The initial objectives and scope of this project were reviewed and defined at a meeting of the Source Sampling Working Committee Grain Dryer Task Force held in Chatham, Ontario on 24 May 1979. Technical and financial requirements and limitations were discussed by

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On the basis of the preliminary discussions, two alternate schemes for particulate collection were designed for consideration by Dorssers Welding Company Limited, Chapman Farm Equipment and the Ontario Ministry of the Environment, Air Resources Branch, Source Assessment Unit.

A second meeting was held in Woodstock, Ontario on 14 September 1979. Modifications to the original plans were suggested by various members of the group which included

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A. Objective

The objective of this investigation was to determine the total particulate matter emission rate from an "ACE" Model 2165-D grain dryer equipped with Behlen "Rotovac" pollution control equipment and to relate it to the operating parameters of the unit. The study was to be carried out on a new installation built by Dorssers Welding Company Limited for St. Clair Grain and Feeds in Newbury, Ontario.

B. Scope

The testing program included determination of

- i. Q_s , average volumetric stack gas flow rate on a dry basis at reference conditions, ft^3/hr

- ii. C_p , concentration of particulate matter in stack gas on a dry basis at reference conditions, lb_m/ft^3
- iii. ER_p , emission rate of particulate matter from a stack on a dry basis at reference conditions, lb_m/hr
- iv. particle size distribution of particulate matter in the effluent gases
- v. volumetric flow rate of effluent gases for each air filter unit
- vi. temperature of ambient air
- vii. humidity of ambient air
- viii. temperature of effluent gases
- ix. wind speed and direction
- x. grain throughput
- xi. weight of filter-cyclone catch
- xii. grain quality before drying
- xiii. grain quality after drying
- xiv. natural gas consumption rate
- xv. electrical power consumption
- xvi. dryer temperatures at the
 - plenum
 - top
 - middle
 - cooling section overhead

for three (3) complete tests, carried out according to the Ontario Ministry of the Environment Source Testing Code, on the dryer filter system.

II. PRINCIPLES OF GRAIN DRYING

The artificial drying of grain is a very important phase of harvesting because it helps to minimize losses due to spoilage during storage.

Because commercial grain dryers are sometimes located near residential areas their operations become of concern to the Ontario Ministry of the Environment. Emissions of dust from grain dryers occur during loading, unloading, and drying. The air pollution associated with loading and unloading operations can be controlled through improved housekeeping. Minimization of particulate emissions during drying requires modification of the drying process itself or installation of appropriate pollution control equipment.

The air pollution problems associated with grain dryers in Ontario can be discussed in terms of

- i. the basic designs of commercial dryers
- ii. the types of grains that are handled
- iii. the necessity of grain drying.

A. Commercial Grain Dryer Designs

Essentially, all commercial dryer designs provide for wet grain to flow continuously downward by gravity through perforated or screen type grain columns. The drying zone, which is about the top two-thirds of the column, is heated with warm air from the warm air plenum. The bottom third, functioning as the cooling zone, receives an air stream from the cool air plenum.

Drying rates are controlled by regulating the grain flow through the columns with metering augers at the base of each column. Temperature sensing instrumentation in the grain column near the air exhaust side activates the metering augers.

The directions of air and grain flow inside the dryer define three basic dryer modes. Figure 1 illustrates the fundamental differences among cross flow, concurrent flow and counter flow operations [1].

1. Cross Flow Units [1]

With drying air flowing at right angles to the flowing grain it takes about 1/2 hour of residence time for the grain

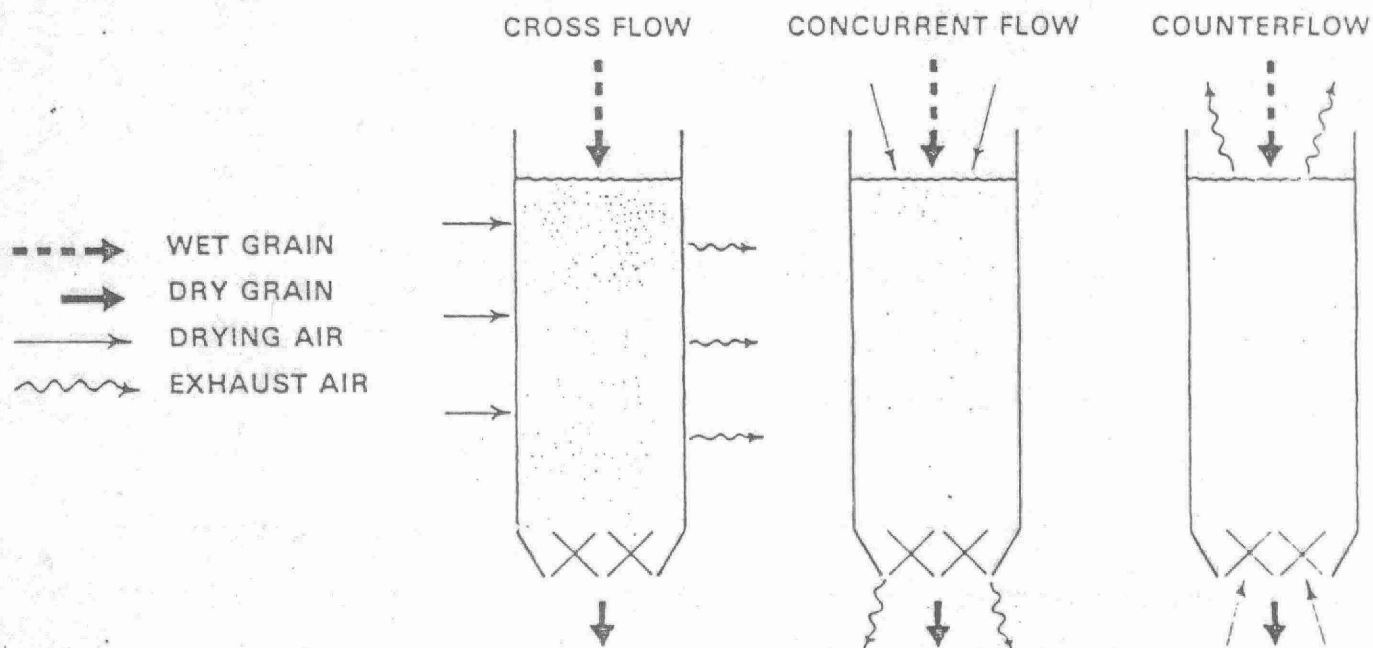


FIGURE 1: Directions of Grain and Air Flow in the Three Basic Types of Commercial Grain Dryers [1]

nearest the hot air plenum to attain the temperature of the drying air. As a result, the grain close to the hot air plenum can be overdried if it is exposed to hot, dry, incoming air for the entire drying period. On the other hand, the grain on the opposite side of the column can be underdried if exposed to only cool, moist exhaust air. To minimize such undesirable gas-solid contacting, manufacturers usually provide one or two grain inverters in each column. These devices promote movement of grain from the drying to the exhaust sides and from the exhaust to the drying sides of the column in an effort to maximize uniform water removal [2]. The essential features of a typical grain inverter are illustrated in Figure 2.

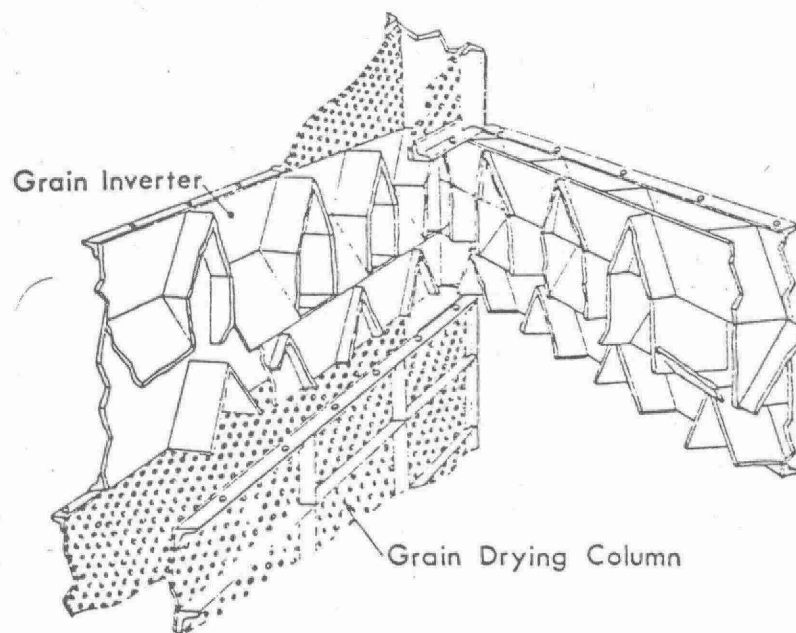


FIGURE 2: Diagram of the Interior of a Grain Inverter [2]

Average grain and exhaust air temperatures increase from the top to the bottom of the drying zone of each unit. However, the average equilibrium moisture content, or level to which the air could dry the grain, decreases from top to bottom.

Thermal stresses that develop in the dried grain are relieved in the cooling zone.

2. Concurrent Flow Units [1]

By design, both the drying air and grain flow in the downward direction. As a result, the grain temperature is higher during the initial part of the drying period than with other contacting modes. Since the wettest grain is contacted with the hottest drying air most of the moisture is removed during this initial drying stage. There is considerable cooling of the drying air as this moisture vaporizes.

The relative humidity of the air and the equilibrium moisture content increase from top to bottom of the drying zone. Since the drying air and grain attain the same temperature rather quickly thermal stresses in the grain are relieved during the drying phase itself. As a result stress cracking can be minimized by this approach.

3. Counterflow Units [1]

According to this design, drying air moves upward against the downward flowing grain. Heat exchange occurs along

the entire length of the drying-zone. This provides an essentially constant rate of moisture removal. The cooled exhaust air leaves at about the wet bulb temperature of the incoming air while the dried grain is discharged at a temperature slightly below that of the incoming air.

The counter flow drying principle yields the highest moisture removal per unit length of drying bed.

B. Varieties of Grain Requiring Drying

Almost all grains could require drying if delivered to storage facilities with excess moisture. However, corn is probably the single species that always must be dried. Field run soybeans are also good candidates for the drying process.

Sampling for particulate emissions from uncontrolled dryers can be a fairly complex problem. When corn is dried the solid particle emissions can be relatively large, but very light and hard to collect. Beeswings, which are also known as Red-dog, are discharged as a light flaky material with specific gravity of 0.70 to 1.2. This thin waxy solid which holds the corn kernel to the cob normally falls from the kernels during drying and handling. In addition to the beeswings, the dust emitted during corn drying will consist of hulls, cracked grain, weed seeds and field dirt.

Atmospheric emissions from uncontrolled dryers handling soybeans are often highly visible because of the high field dust content.

C. Importance of Corn Drying [3]

Corn must be dried before storage in order to lower the kernel moisture content below levels at which microbial action can occur at any appreciable rate. The quality of corn is reduced by fungi or moulds because they

- i. lower the dry weight of stored corn through digestion of dry matter
- ii. can produce mycotoxins that are dangerous when consumed by animal or humans
- iii. destroy oils and other organics in corn kernels
- iv. produce heat as a result of their activity, which helps to accelerate their reaction rate.

Experimental evidence shows that microbial activity is more dependent on the relative humidity of the air between grain kernels than on the moisture content of the grain itself. For relative humidities below 62% there is virtually no mould growth. Since grain moisture content and relative humidity relationships are temperature dependent, it becomes necessary to produce kernels with decreasing moisture contents as higher storage temperatures are anticipated. Table 1 lists the possible storage periods for corn of varying moisture contents that is aerated during storage and has been cleaned but not blended.

The quality of corn depends not only on storage time, but also on the drying temperature and the rates of drying and cooling. The standard of corn quality that must be achieved will be determined by the ultimate use of the dried grain.

Moisture Content %	Storage Time
15	November to April (or less)
14	November to June
13	November to late summer
12	One to several years

TABLE 1: Recommended Moisture Levels in Corn for Various Storage Times [3]

1. Uses of Corn

a. Animal Feed

According to Daynard [3], the largest proportion of the artificially dried corn in Ontario is used for livestock feed as a source of carbohydrates and basic amino acids, including the important member, lysine. Monogastric species such as fowl and swine depend on the lysine in corn for protein synthesis because their systems cannot produce lysine. On the other hand cattle are less dependent on lysine in their food because rumen microorganisms help to synthesize this amino acid in the ruminant animal system.

b. Industrial Processes

i. Wet Milling

Figure 3 summarizes the basic principles of the wet milling process which is the basis of the starch and corn oil industries.

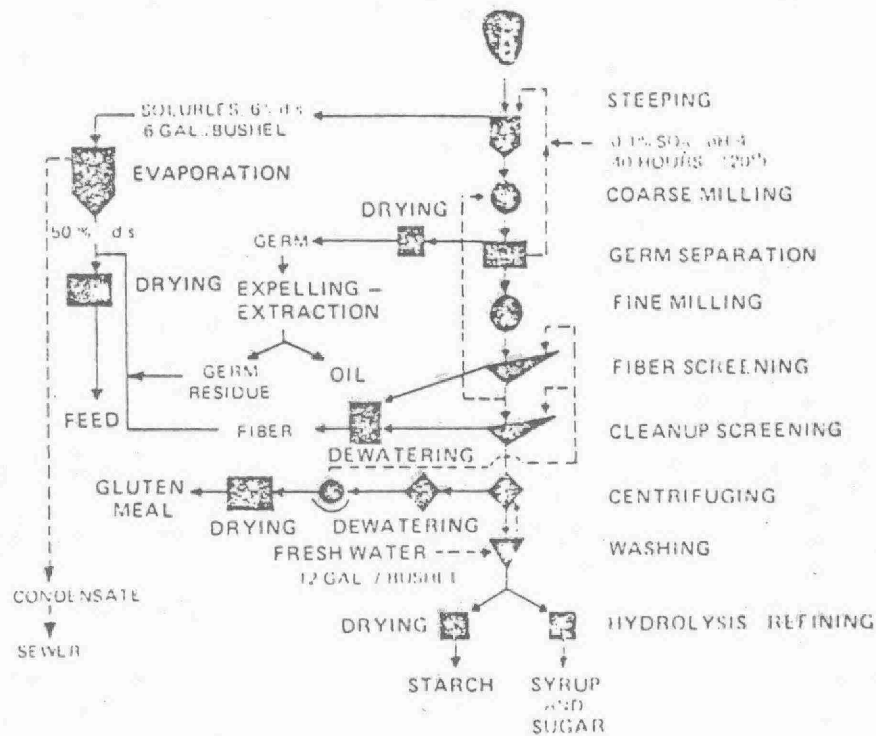


FIGURE 3: Typical Wet Milling Flow Chart [4]

Corn kernels, that have been softened by soaking for 35-40 hours in warm water, are coarse milled in order to separate the oily germ from the hulls and endosperm consisting of starch and gluten. Fine milling of the degerminated material helps to release bound starch and gluten. After separation from the hulls and fine fibres which are used as animal feed, the starch and gluten fraction is centrifuged to yield starch which is washed and dried for sale or converted to sugars and syrups.

Experience shows that naturally dried, well matured corn provides the highest yield of starch [5].

ii. Dry Milling

The dry milling process is used for the production of grit and meal.

iii. Distilling

Corn is one of the principal grains used in fermentation processes for the manufacture of distillers alcoholic products.

2. Dependence of Corn Quality on Drying Parameters

The upper limit of the drying temperature depends on the intended use of the corn being dried.

a. Animal Feed

Experimental evidence [3] indicates that kernel temperatures above 200°F can affect the nutritional value of corn because the important amino acid, lysine, begins to complex with sugar molecules to produce organic species that cannot be digested by domestic animals. This binding appears to be more serious with high moisture corn (30-35%) than with intermediate moisture corn (20-25%) being dried. However, kernels with 25% moisture content can be subjected to temperatures as high as 250°F without loss of nutritional value if used as feed for beef and dairy cattle [3].

Exposure to excessive drying temperatures, which reduce protein availability, can be recognized from the brown discoloration of the kernels which results from sugar caramelization and sugar-lysine complexing [3].

b. Wet Milling

The wet milling process is basically a separation of corn kernels into their protein and carbohydrate components. If kernel temperatures exceed the 140-160°F range, starches gelatinize and also undergo physical binding processes with protein molecules. As a result separation of the starch and protein fractions becomes very difficult.

c. Dry Milling

Artificial drying of corn can create such high temperature and moisture gradients in the kernels that internal fracturing can occur. Candling of individual kernels under an intense light can show stress cracks that are indicative of single, multiple and checked fractures [4]. Stress cracked kernels can disintegrate into several small pieces very readily during subsequent handling. Consequently, stress cracked corn is not good for dry milling where the efficiency depends on the availability of whole kernels for the production of large grits.

Research studies have shown that it is almost impossible to produce stress-free corn during artificial drying if kernel temperatures exceed 100°F. The critical drying period

appears to be during moisture reduction from 18 to 15 percent. If cooler temperatures during this interval can be achieved with two stage or concurrent flow techniques stress cracking can be minimized. Regulation of cooling rates after drying also can help to reduce stress cracking. Dryeration, which is drying with heated air to 16-18% moisture only, has been recommended as a means of reducing stress cracking in corn to be used industrially.

d. Distilling

In order to minimize the decrease in alcohol yield due to the gelatinization of starch and its binding with protein materials, corn kernels should not be exposed to temperatures exceeding the 140-160°F range in cross flow dryers. In concurrent flow units with dryeration higher air temperatures can be tolerated without significant reduction in alcohol yield.

Table 2 lists recommended temperatures for cross flow dryers producing corn for specific uses or with desirable quality standards. Higher temperatures may be used safely with other drying air-grain contacting modes [3].

Grain Use or Quality	Maximum Drying Temperature °F
Animal Feed	
Beef and Dairy Cattle	250°F (25% moisture)
Poultry and Swine	200°F
Industrial Processing	
Avoid starch-protein binding	140-160
Minimize stress-cracking	
without dryeration	100-120
with dryeration*	160-200
Maintain Viability (germination)	120-140
*Drying with heated air to 16-18% moisture, only	

TABLE 2: Maximum Cross Flow Dryer Temperatures for Corn Meeting Specific Market or Quality Standard Requirements [3]

III. PROGRAM DEVELOPMENT

The sampling of grain dryers has been discussed in Ontario since early 1977. No serious attempts were made to carry out any on-site programs because of the difficulties presented by the designs of the exhaust systems of these units. The extensive areas, emitting gases at very low velocities, high above ground level, make representative sampling very difficult if not almost impossible.

Discussions with

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emphasized the design and operating limitations that would have to be incorporated into any proposed sampling strategy.

On-site inspections of a

- i. Fallon Model 1500 grain dryer to be equipped with a Dustell automatic fabric filter system at the Ralston-Purina Company of Canada Limited facility in Woodstock, Ontario
- ii. Fallon grain dryer operated by Yantzi Feed and Grain, Tavistock, Ontario

provided the basis for the design of a realistic sampling program for conventionally operated grain dryers.

The construction of a Dorssers Welding Company Limited "ACE" Model 2165-D grain dryer for St. Clair Grain and Feeds at Newbury, Ontario presented an opportunity to sample a unit that was equipped with Behlen "Rotovac" exhaust air cleaning system located at a reasonably convenient height.

A. Description of "ACE" Model 2165-D Dryer [6]

Figure 4 illustrates the basic design of the "ACE" Model 2165-D dryer, equipped with a Behlen "Rotovac" exhaust air cleaning system, as built by Dorssers Welding Company Limited for the St. Clair Grain and Feeds facility at Newbury, Ontario. This is, essentially, a cross flow unit with dual columns that are 65 feet high, 21 feet long and 1 foot wide. The upper 47 feet serve as the heating zone. Cooling of the grain occurs in the lower 18 foot section.

Heating and cooling air is provided by a single, Dorssers Centrifugal 660-A fan driven by a 150 HP, 550 volt-3 phase motor. Temperature sensing elements were located on the exhaust side of one grain column at 10, 30 and 50 foot distances from the top of the column.

A single grain inverter was provided in each grain column about 20 feet from the upper end.

Table 3 lists other pertinent features of this unit.

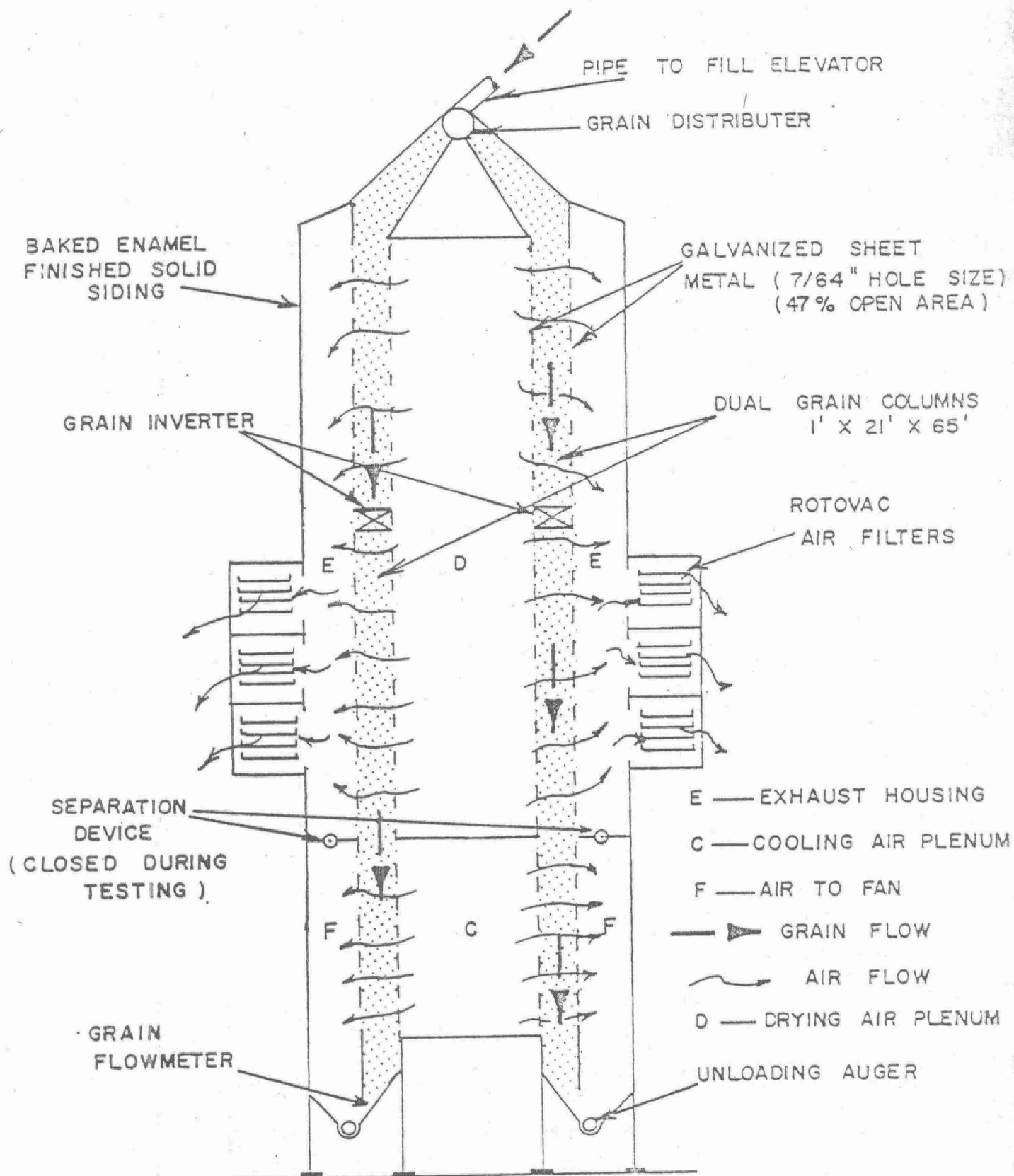


FIGURE 4: Typical Design of an "ACE" Grain Dryer Equipped with "Rotovac" Air Filters

Capacity Based on #2 Corn at 15% Moisture Removal

Throughput	1000 bu/hr
Ambient Temperature	70°F
Temperature Lift	140°F
Drying Temperature	210°F
Garver Bin Capacity	300 bu
Heating Column Capacity	1680 bu
Cooling Column Capacity	504 bu

Screen Characteristics

Panel Size	36" x 120" x 18 Gauge
Weight	37 lb
Hole Size	7/64 in.
Open Area Fraction	0.47
Corrosion Protection	Galvanized

Fan Characteristics

Number	1
Type	Dorssers Centrifugal 660-A
Diameter	66 in.
R.P.M.	614
Motor Size	150 H.P.
Capacity (Heating)	174,720 c.f.m. @ 70°F, 2"W.P.
Air to Product Ratio (Heating)	104 c.f.m./bu
Capacity for Cooling	55,000 c.f.m.
Air to Product Ratio for Cooling	109 c.f.m./bu

Burner Characteristics

Number	1
Type	Maxon NP-1-36-B Airflo
Capacity	35,000,000 B.T.U./hr

Dryer Characteristics

Nominal Operating Temperature	210°F
Dryer Efficiency	1750 B.T.U./lb _m water removed
Fuel Heating Value	1000 B.T.U./ft ³
Fuel	Natural Gas

Recirculation

Cooling Air Recirculated	55,000 c.f.m.
--------------------------	---------------

Burner Control Characteristics

Ignition System	Honeywell
Thermostats	1
Thermostat Location	In Heating Plenum

Temperature Monitor Characteristics

Type	Honeywell
Number	1
Location	In Heating Plenum

Flow Control Characteristics

Metering Type	Electrical Modulating Valve Maxon "CV" Valve Connected to Honeywell Motor
---------------	---

Total Electrical Power (Dryer Only)

150 + 2 + $\frac{3}{4}$ H.P.
Blower: 150 H.P.
Screw Conveyor: $\frac{3}{4}$ H.P.
Metering Rolls: $\frac{1}{4}$ H.P.

TABLE 3: Design Characteristics of "ACE" Model 2165-D Dryer
in Newbury, Ontario

B. Description of Behlen "Rotovac" System [8]

The "ACE" dryer in Newbury, Ontario is the first unit to be equipped with a Behlen "Rotovac" pollution control system. Figures 5 and 6 illustrate the basic principles of the "Rotovac" installation associated with the "ACE" Model 2165-D grain dryer built for St. Clair Grain and Feeds.

The "Rotovac" system provides a modular approach to control of the particulate matter in grain dryer emissions. Particulate laden air from the dryer exhaust housing is directed onto the outer surfaces of 6 rotating filter cages turning at 2 r.p.m. Solid material is collected on 62 mesh polyester screening. Vacuum nozzles, spanning the length of each rotating drum, continuously remove Beeswings and other solids from the filter surfaces. The scavenged materials are collected in high efficiency cyclones as waste to be removed to a landfill site. The cleaned dryer exhaust gases are discharged to the atmosphere through front and rear exhaust louvres on each side of the dryer.

Table 4 summarizes the pertinent features of a typical "Rotovac" module.

C. Modifications Required for Sampling Program

1. Initial Proposal

Figures 7 and 8 illustrate the initially proposed modification to the Model 2165-D dryer - Behlen "Rotovac" system for sampling purposes. This approach called for the

Chapman's BEHLEN ROTOVAC INSTALLATION

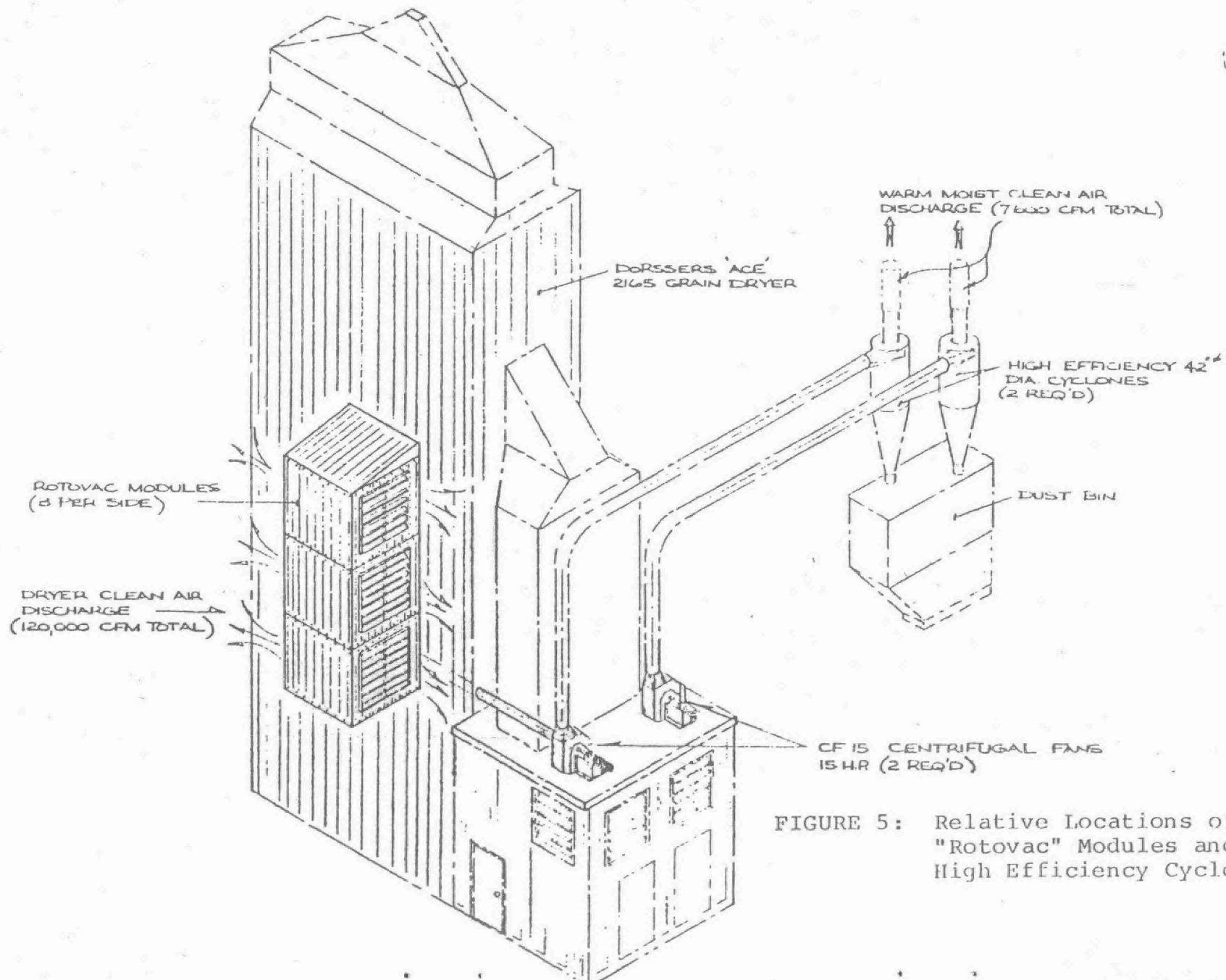


FIGURE 5: Relative Locations of "Rotovac" Modules and High Efficiency Cyclones [8]

TYPICAL ROTOVAC INSTALLATION (3 MODULES)

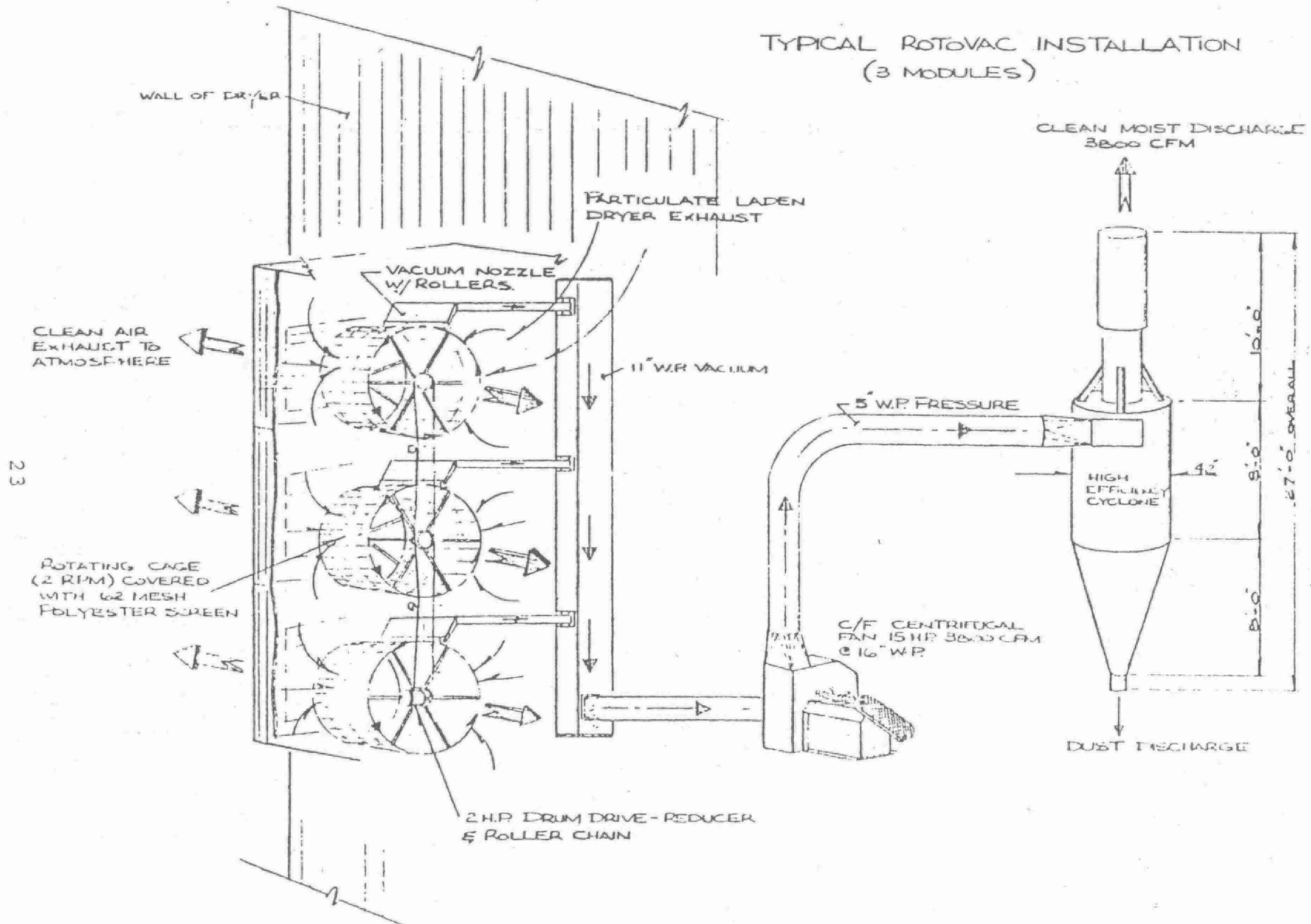


FIGURE 6: Typical "Rotovac" Installation [8]

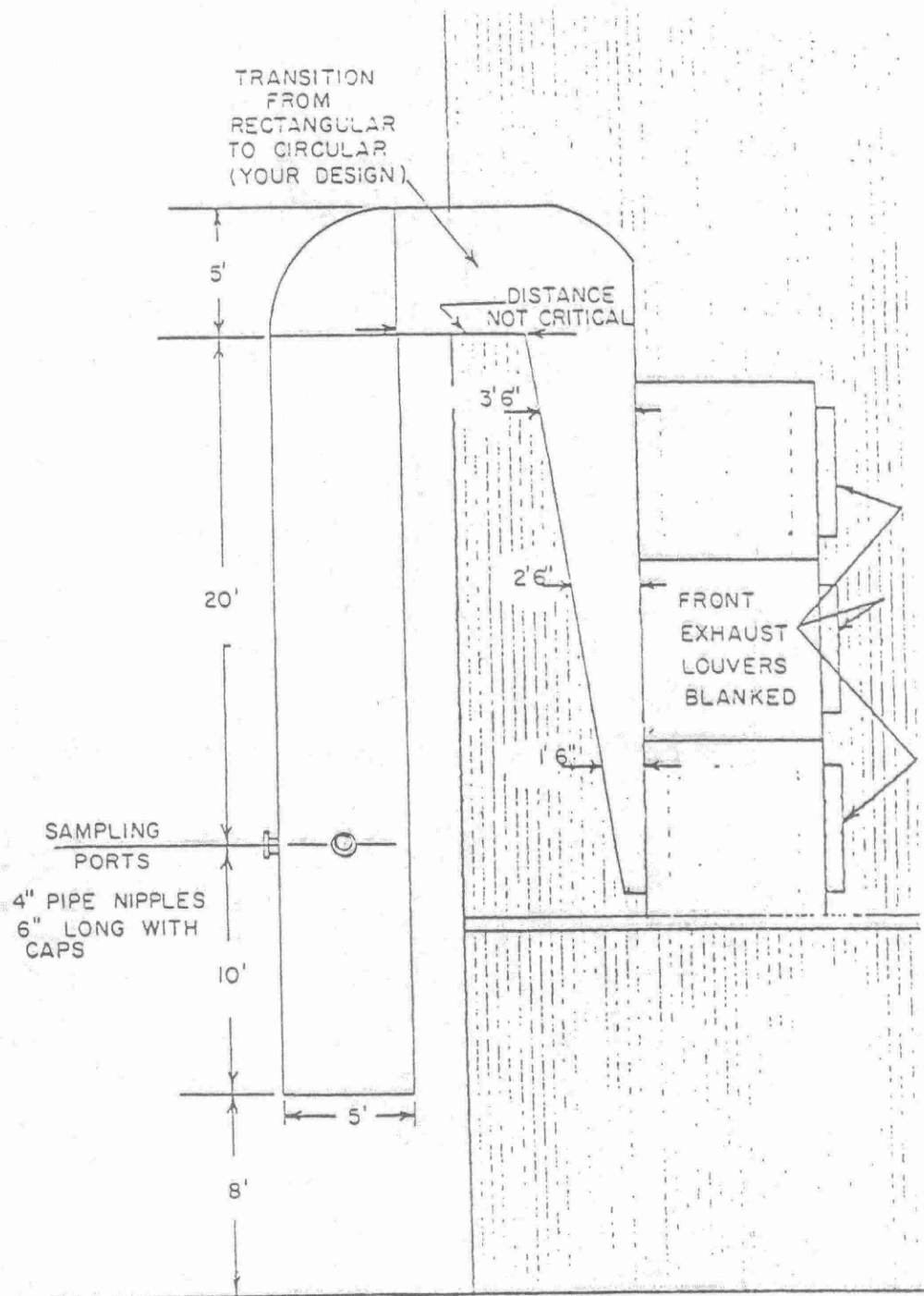


FIGURE 7: Side View of Dryer with Proposed Sampling Manifold

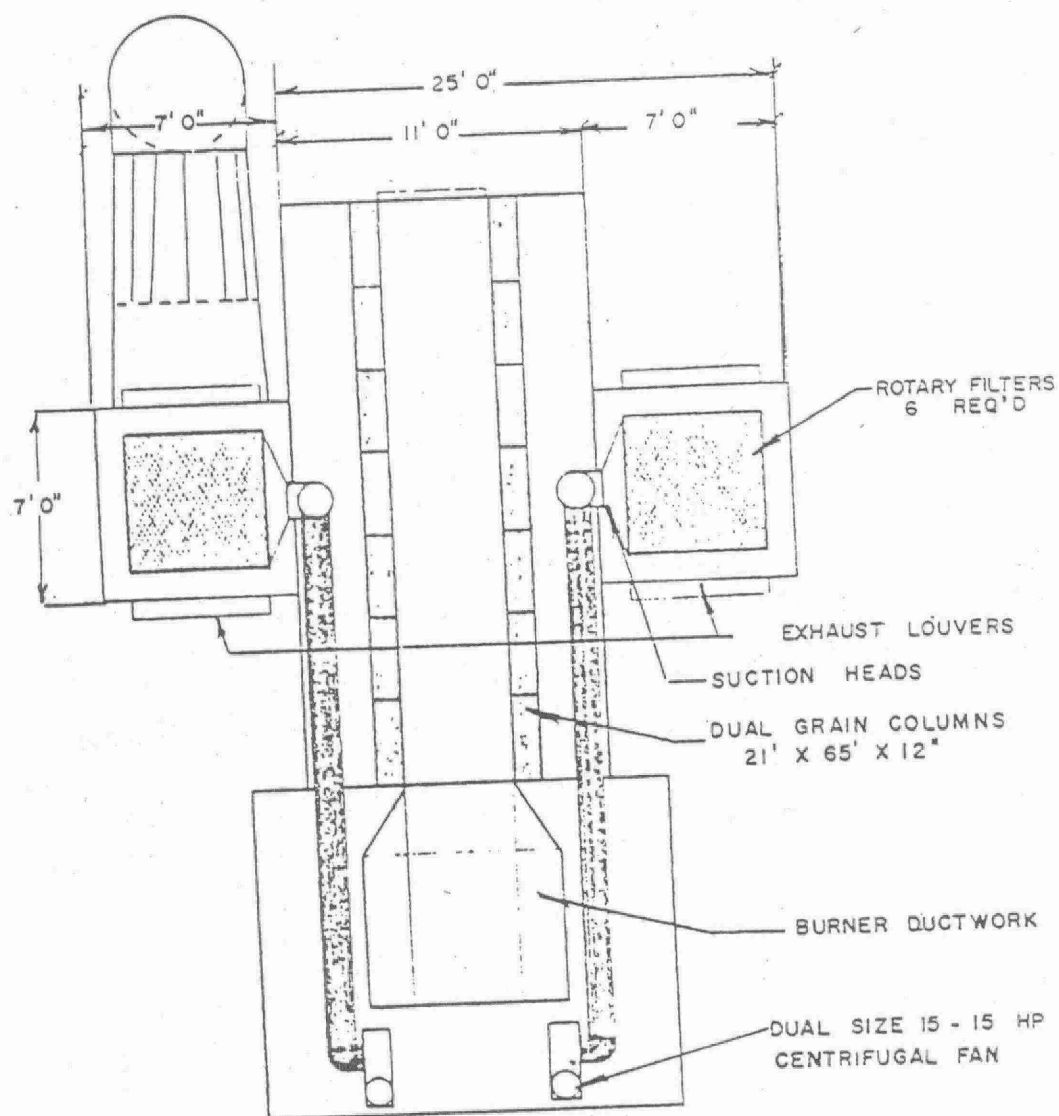


FIGURE 8: Plan View of Dryer with Proposed Sampling Manifold

Drum Size	60 in. diameter x 48 in. length
Drum Speed	2 r.p.m.
Cloth Type	62 mesh polyester screen (270 micron)
Air Flow/Module	20,000 c.f.m.
Vacuum Flow/Module	1250 c.f.m. @ 16 in. W.P.
Air/Cloth Ratio	330 c.f.m./ft ²
Fan Capacity/Module	1250 c.f.m. @ 16 in. W.P.
Drum Drive (Main)	2 H.P. reducer and motor
Drum Drive (Secondary)	roller chain from main
Pressure Drop Across Drum	$\frac{1}{4}$ - $\frac{1}{2}$ in. W.P.

TABLE 4" "Rotovac" Module Specifications [8]

blanking of all exhaust louvres on both front ends and one rear end of the "Rotovac" air filters and attaching a portable manifold over the remaining three open, rear exhaust louvres. A crane would move the sampling manifold from one side of the dryer to the other for completion of one test.

A complete test would have involved particulate sample collection from two sides of the dryer using a total of 48 points along 2 perpendicular traverses in the vertical stack section through which exhaust gases would flow in a downward direction.

During the meeting of 24 May 1979 there was concern expressed that considerable preliminary work would be required to insure a balanced dryer operation. It was felt that resistance to gas flow could be altered by the presence of the manifold on only one side of the system during testing. In addition, this approach required heavy financial commitments for standby manpower and mechanical equipment to move the manifold from one side of the dryer to the other during on-site testing periods.

2. Acceptable Modification

Considerations of balanced dryer operation during sampling dictated that identical modifications should be made to both sides of the dryer. The desired conditions were achieved by blanking all 3 front or all 3 back louvres on alternate sides of the dryer and attaching a 4 foot length of 3 foot x 3 foot horizontal ducting to each of the open exhaust filter louvres at the rear and front of the dryer respectively. Figures 9 and 10 illustrate the arrangement of sampling duct extensions and specifications for flow straighteners that were installed inside each extension. The design of the horizontal sampling extensions represented a balance between costs of fabrication and erection of the components and compliance with the Ontario Source Testing Code [9].

According to this approach a complete test would involve particulate sample collection from the 6 horizontal ducts mounted on 2 sides of the dryer. Installation of the egg-crate flow straighteners in each sampling duct extension provided

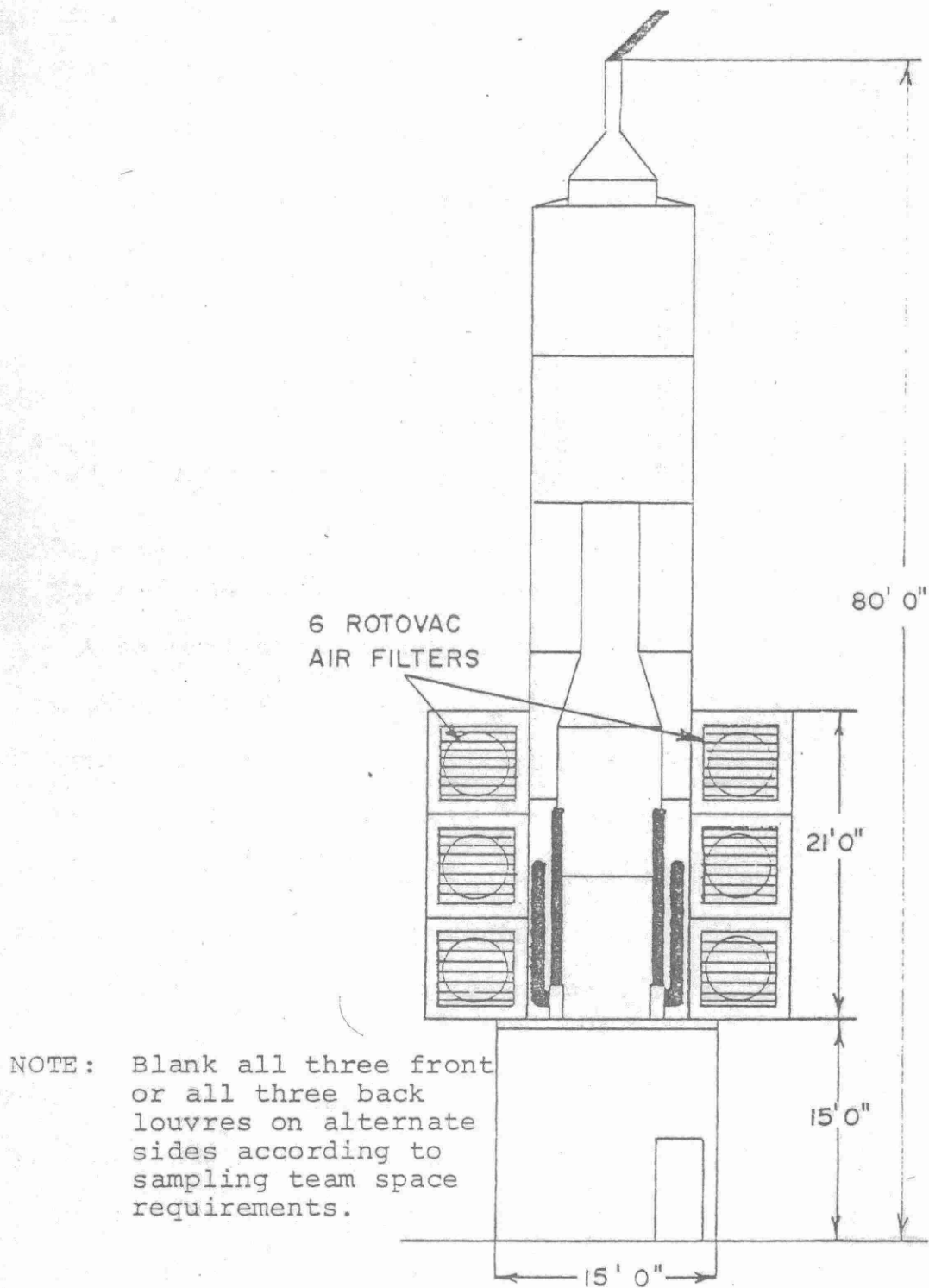
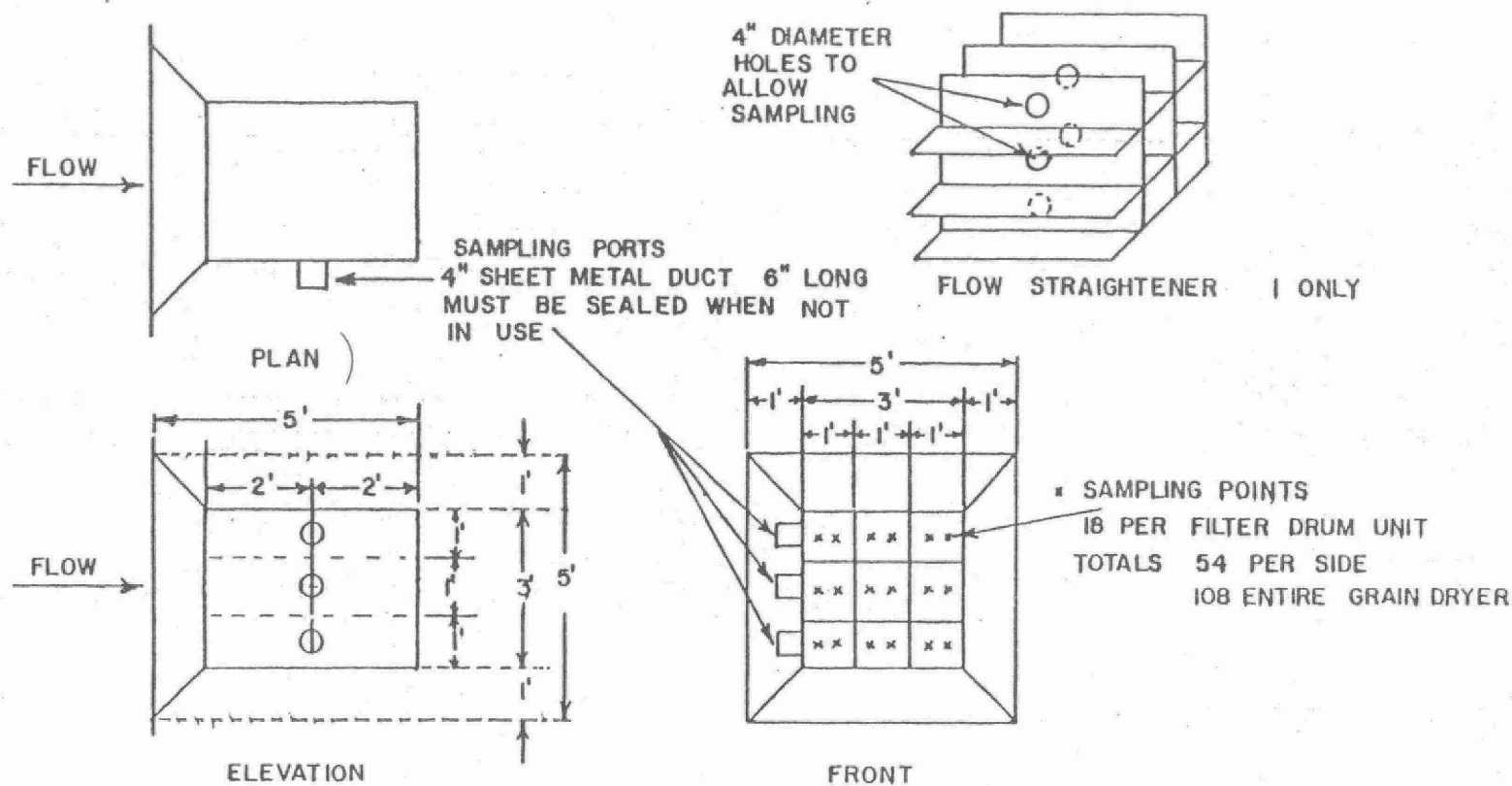


FIGURE 9: Front View of Dryer



SAMPLING DUCTS ONE PER ROTOVAC AIR FILTER 6 TOTAL

SCALE 3/8" = 1 FOOT

FIGURE 10: Specifications for Sampling Duct Extensions

convenient 1 ft² sampling areas in which 2 sampling points were spaced at 4 inch intervals as illustrated in Figure 10. A total of 108 sampling points would insure representative sample collection. The locations of the sampling points in the extensions, essentially 2 equivalent diameters upstream and downstream of flow disturbances, should provide for representative sample acquisition because

- i. sampling would be downstream of a converging section
- ii. flow straighteners would be installed in each duct
- iii. the particle size distribution after control equipment should help to minimize maldistribution of the solid emissions.

IV. THE TESTING PROGRAM

Figures 11 and 12 illustrate the relative locations of blanked exhaust louvres with respect to sampling duct extensions as viewed from the front and rear of the dryer respectively.

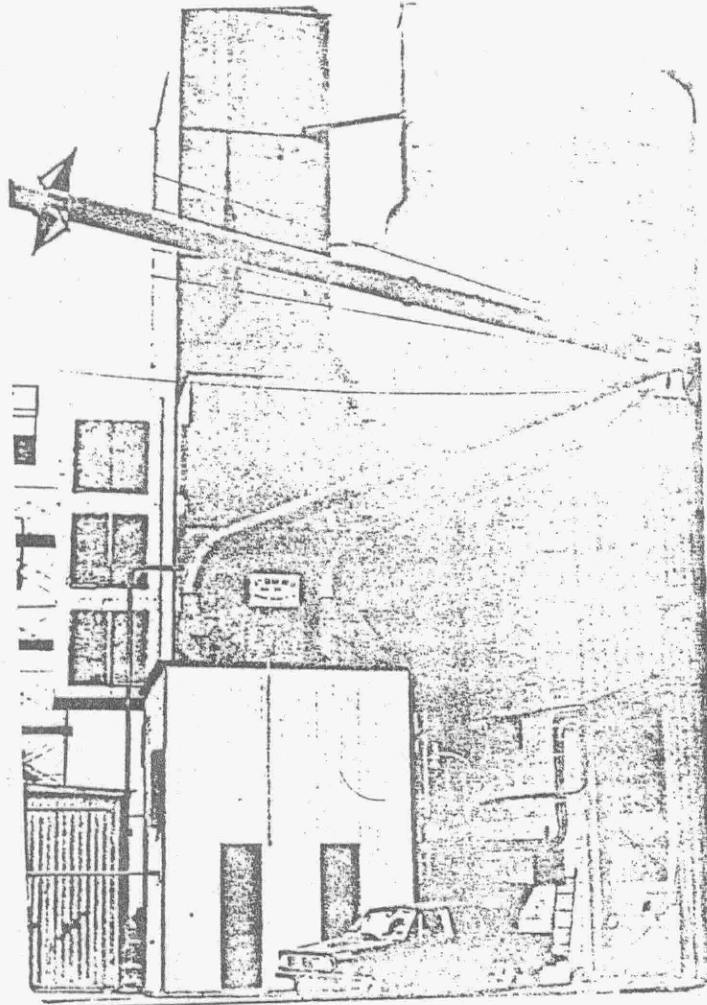


FIGURE 11: Front View of Modified Dryer Installation

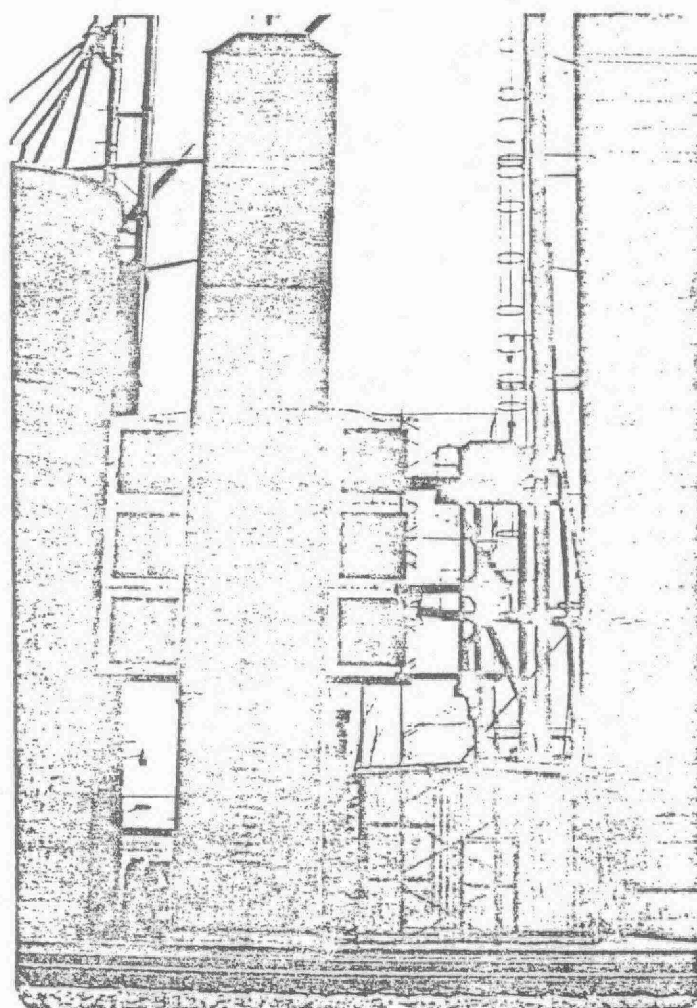


FIGURE 12: Rear View of Modified Dryer Installation

Details of the sampling duct extensions have been provided in Figure 10.

A. Preliminary Procedures

1. On-Site Inspection

A personal inspection of the physical characteristics of the dryer installation was conducted on 19 October 1979 to

- i. check out instrumentation for measuring prevailing wind speeds and directions
- ii. assess the location of scaffolding in terms of sampling needs
- iii. design an adapter for the sampling ports
- iv. specify location of electrical power outlets
- v. finalize grain sample acquisition strategy for St. Clair Grain and Feed personnel
- vi. finalize gas meter and electrical power data acquisition strategy for St. Clair Grain and Feed personnel
- vii. arrange for clean room facilities for on-site sample recovery and sampling train component replacement
- viii. measure pertinent dimensions at the three metal sampling platforms on the east elevator structure for the design of a probe holder and support for the impinger case
- ix. perform preliminary velocity traverses with and without egg-crate flow straighteners in the sampling duct extensions.

2. Preliminary Survey

On the basis of the preliminary velocity traverses carried out with and without the egg-crate flow straighteners in the sampling duct extensions, recommendations were made for the installation of flow straighteners in all six sampling duct extensions.

A preliminary survey was carried out on 24 October 1979 to assess

- i. the positioning of scaffolding
- ii. the suitability of the sampling port adapter
- iii. the probe support system
- iv. the impinger case support system
- v. the moisture content of exhaust gases
- vi. the velocity distributions in another sampling duct extension fitted with an egg-crate flow straightener.

B. Compliance Testing

The design of the sampling strategy was based on meeting Ontario Ministry of the Environment Compliance Test requirements. All tests were carried out according to the Ontario Source Testing Code procedures [9] except for the number and location of sampling points which were established in consultation with Ministry of the Environment personnel.

1. Instrumentation

The sampling train employed for solid particulate matter acquisition was manufactured by the Western Precipitation Division of Joy Manufacturing and sold under the trade name "Emission Parameter Analyzer". The components of this system are represented schematically in Figure 13. This model is approved by the Ministry of the Environment, Province of Ontario and the U. S. Environmental Protection Agency.

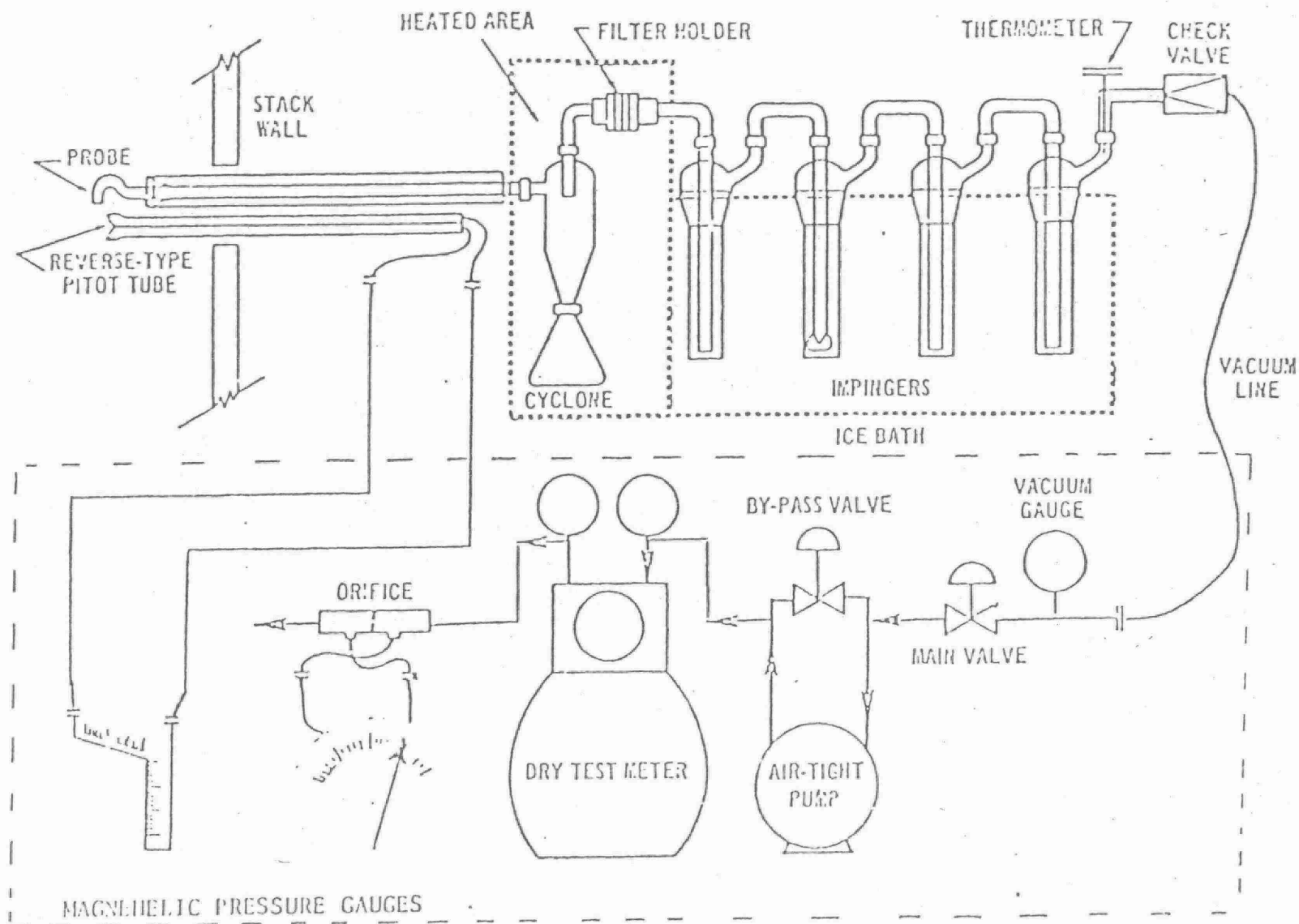


FIGURE 13: Particulate Matter Sampling Train

In order to insure accurate measurements with the sampling train, the S-type pitot tube-sampling nozzle combination, orifice rate meter and dry total gas meter were calibrated according to standard procedures [10]. The calibration data are listed in Appendix I.

Because of the low gas velocities encountered during the preliminary survey the Magnehelic pressure gauge associated with the S-type pitot tube was replaced with an inclined manometer.

2. Number and Location of Sampling Points

All velocity and particulate matter loading evaluations were made from data collected at 6 points along each of 3 vertically stacked traverses in each of the 6 sampling duct extensions. Figure 14 illustrates the code established for identifying the 108 sampling points used for data acquisition. The relative locations of the 9 sampling ports on the 3 sampling duct extensions at the rear of the dryer are shown in Figure 15.

3. Sampling Time Per Point and Gas Sample Volume

Sampling times of $2\frac{1}{2}$ minutes per point for solid particulate matter loading determinations were selected to provide sufficient material for weighing purposes. Gas sample volumes corresponded to approximately 110 cubic feet for each loading test.

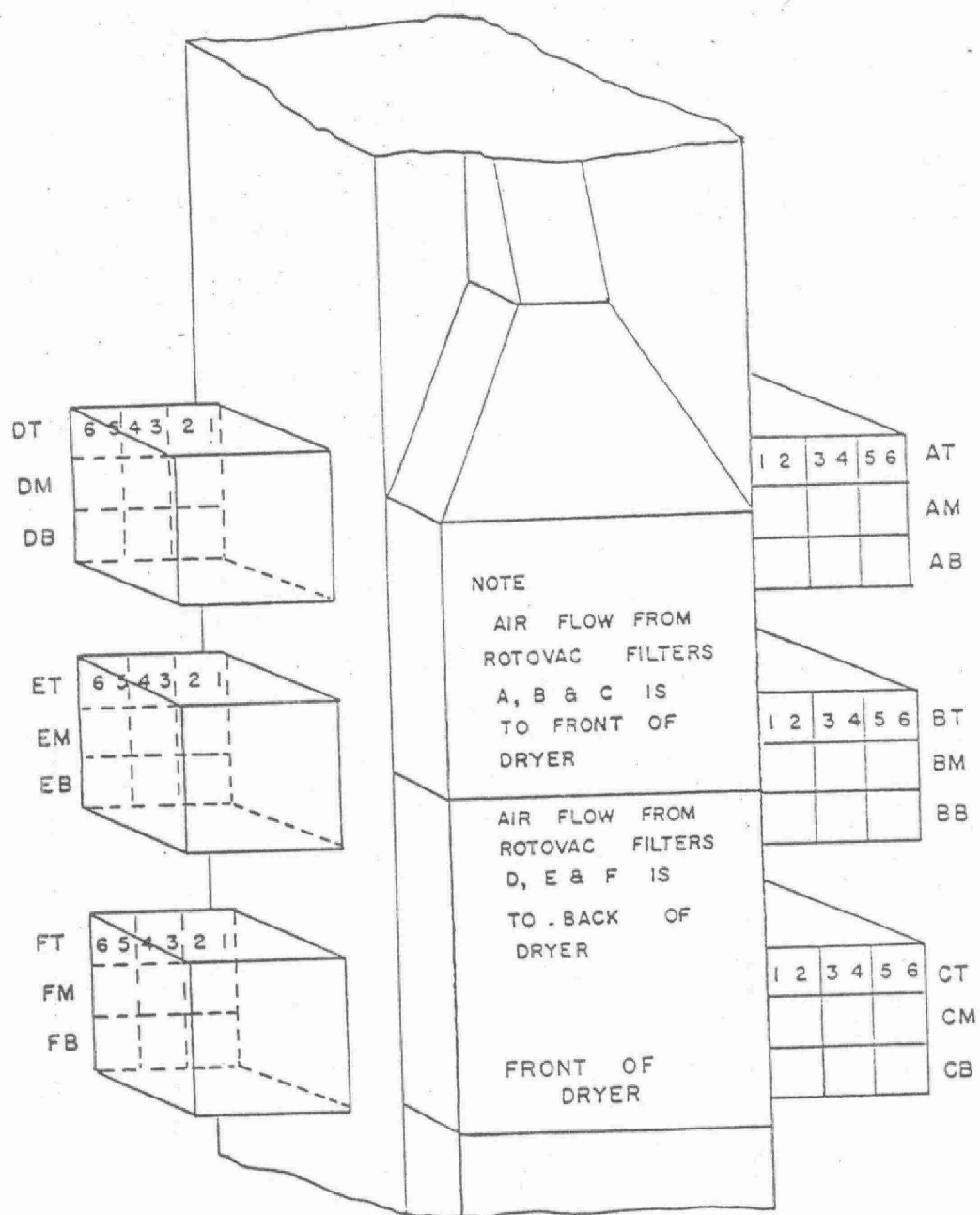


FIGURE 14: Identification of Individual Sampling Points

4. Mode of Traversing

The cumulative sampling technique was employed for solid particulate acquisition from the 108 sampling points. Each test commenced with sampling at point AT1 in the top sampling duct extension at the front of the dryer and ended at point FB6 in the bottom sampling duct extension at the rear of the unit.

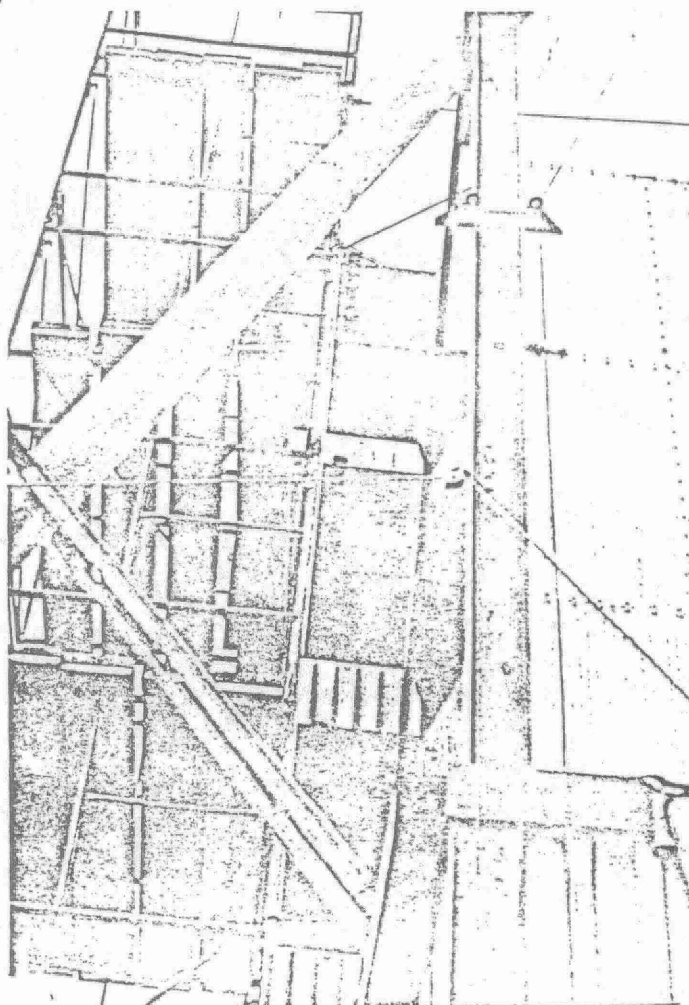


FIGURE 15: Relative Location of Sampling Ports at Rear of Dryer

5. Sample Recovery

After sampling a set of 3 duct extensions at the front or back of the dryer, the contents of the first 3 impingers were emptied and washed into polyethylene bottles which were sealed until sample analysis in Windsor, Ontario.

The nozzle, probe and cyclone catches were also collected in polyethylene bottles for subsequent analysis in Windsor. The used filter assemblies were simply replaced with clean units. Filter recovery was accomplished in the Windsor, Ontario laboratory.

6. Liaison with Ministry of the Environment

The design of the sampling duct extensions and location and number of sampling points were reviewed and authorized by

Mr. J. McDonald, P.Eng.
Mr. V. Ozvacic, P.Eng.
Source Assessment Unit
Air Resources Branch
Ministry of the Environment
880 Bay Street, 4th Floor
Toronto, Ontario M5S 1Z8

before the sampling strategy was finalized.

During the sampling program personal inspections were conducted by

- i. Mr. W. P. Suboch, P.Eng.
Head, Food and Forest Unit
Waste Management Branch
Ministry of the Environment
135 St. Clair Avenue West, 2nd Floor
Toronto, Ontario M4V 1P5
(Friday, 26 October 1979)

- ii. Mr. J. T. Manuel, P.Eng.
District Officer
Industrial Abatement
Southwestern Region
Ministry of the Environment
985 Adelaide Street, South
London, Ontario N6E 1V3
(Saturday, 27 October 1979)
- iii. Mr. O. Wigle, P.Eng.
Senior Environmental Officer
Southwestern Region
Ministry of the Environment
985 Adelaide Street, South
London, Ontario N6E 1V3
(Friday, 2 November 1979)
- iv. Mr. R. Benjamin
Environmental Protection Service
Environment Canada
Ottawa, Ontario
(Friday, 2 November 1979)

V. RESULTS

Raw test data and pertinent calculations are provided in Appendix II.

A. Preliminary Survey Testing

Tables 5 and 6 summarize the preliminary velocity data obtained from two different sampling duct extensions. Extension A was equipped with egg-crate flow straighteners. The absence of flow straighteners in sampling duct extension B provided a means of evaluating the effectiveness of these devices in terms of their ability to improve velocity profiles in the regions of the sampling points.

Table 7 illustrates the velocity distributions in sampling duct extension C without flow straighteners when the plant was operating under normal conditions. The effect of introducing the egg-crate flow straighteners into extension C is shown in Table 8.

B. Compliance Testing

Table 9 summarizes the results of 3 compliance tests. The data were analyzed to show

- i. the volumetric flow rate
- ii. the moisture content
- iii. the emission rate

for each filter module.

Sampling Point Location	U_{Local} ft/sec	$\frac{U_{\text{Local}}}{U_{\text{Average}}}$	Sampling Point Location	U_{Local} ft/sec	$\frac{U_{\text{Local}}}{U_{\text{Average}}}$	Sampling Point Location	U_{Local} ft/sec	$\frac{U_{\text{Local}}}{U_{\text{Average}}}$
AT1	13.2	0.75	AM1	21.9	1.25	AB1	29.0	1.66
AT2	11.5	0.66	AM2	22.3	1.27	AB2	26.3	1.50
AT3	5.0	0.29	AM3	24.0	1.37	AB3	26.6	1.52
AT4	4.1	0.23	AM4	19.1	1.09	AB4	24.4	1.39
AT5	4.1	0.23	AM5	12.8	0.73	AB5	26.9	1.54
AT6	5.7	0.33	AM6	15.2	0.78	AB6	23.0	1.31
Mean	7.3	0.42 ± 0.23	Mean	19.2	1.08 ± 0.27	Mean	26.0	1.49 ± 0.12
$T_s = 80^\circ\text{F}$ $P_s = 29.92 \text{ in-Hg}$ $M_s = 28.9 \text{ lb}_m/\text{lb mole}$ $U_{\text{Average}} = 17.5 \text{ ft/s}$ $\left(\frac{U_{\text{Local}}}{U_{\text{Average}}} \right)_{\text{Average}} = 1.00 \pm 0.50$ Wind Speed = 17 mph								

TABLE 5: Preliminary Velocity Traverses with Flow Straighteners

Sampling Point Location	U_{Local} ft/sec	$\frac{U_{\text{Local}}}{U_{\text{Average}}}$	Sampling Point Location	U_{Local} ft/sec	$\frac{U_{\text{Local}}}{U_{\text{Average}}}$	Sampling Point Location	U_{Local} ft/sec	$\frac{U_{\text{Local}}}{U_{\text{Average}}}$
BT1	9.1	0.44	BM1	26.3	1.18	BB1	32.0	1.55
BT2	8.1	0.39	BM2	20.7	1.00	BB2	33.5	1.63
BT3	5.7	0.28	BM3	23.7	1.15	BB3	36.3	1.76
BT4	2.6	0.13	BM4	20.7	1.00	BB4	34.5	1.67
BT5	negative	0	BM5	20.7	1.00	BB5	37.2	1.81
BT6	1.8	0.09	BM6	21.9	1.06	BB6	35.4	1.72
Mean	4.55	0.22±0.18	Mean	22.3	1.07±0.08	Mean	34.8	1.69±0.09
$T_s = 80^\circ\text{F}$ $P_s = 29.92 \text{ in-Hg}$ $M_s = 28.9 \text{ lb}_m/\text{lb mole}$ $U_{\text{Average}} = 20.6 \text{ ft/s}$ $\left(\frac{U_{\text{Local}}}{U_{\text{Average}}}\right)_{\text{Average}} = 1.00 \pm 0.63$ Wind Speed = 17 mph								

TABLE 6: Preliminary Velocity Traverses Without Flow Straighteners

Sampling Point Location	U_{Local} ft/sec	$\frac{U_{\text{Local}}}{U_{\text{Average}}}$	Sampling Point Location	U_{Local} ft/sec	$\frac{U_{\text{Local}}}{U_{\text{Average}}}$	Sampling Point Location	U_{Local} ft/sec	$\frac{U_{\text{Local}}}{U_{\text{Average}}}$
CT1	8.7	0.47	CM1	22.2	1.21	CB1	31.8	1.73
CT2	5.7	0.31	CM2	16.1	0.88	CB2	31.8	1.73
CT3	4.6	0.25	CM3	27.8	1.51	CB3	30.8	1.67
CT4	0	0	CM4	27.8	1.51	CB4	32.1	1.74
CT5	3.3	0.18	CM5	13.1	0.71	CB5	30.4	1.65
CT6	4.6	0.25	CM6	15.4	0.84	CB6	24.6	1.34
Mean	4.5	$0.24 \pm .15$	Mean	20.4	1.11 ± 0.35	Mean	30.3	1.64 ± 0.15
$T_{\text{Dry Bulb}} = 100^{\circ}\text{F}$ $T_{\text{Wet Bulb}} = 88^{\circ}\text{F}$ $B_{W0} = 0.036$ $N_s = 28.51 \text{ lb}_m/\text{lb mole}$ $U_{\text{Average}} = 18.4 \text{ ft/s}$ $\left(\frac{U_{\text{Local}}}{U_{\text{Average}}} \right)_{\text{Average}} = 1.00 \pm 0.63$ Sampling Probe - S-Type Pitot Tube Used								

TABLE 7: Preliminary Velocity Data Without Flow Straighteners for Operational Dryer

Sampling Point Location	U_{Local} ft/sec	$\frac{U_{\text{Local}}}{U_{\text{Average}}}$	Sampling Point Location	U_{Local} ft/sec	$\frac{U_{\text{Local}}}{U_{\text{Average}}}$	Sampling Point Location	U_{Local} ft/sec	$\frac{U_{\text{Local}}}{U_{\text{Average}}}$
CT1	5.6	0.28	CM1	24.4	1.19	CB1	34.2	1.67
CT2	4.6	0.23	CM2	24.4	1.19	CB2	33.9	1.66
CT3	4.6	0.23	CM3	24.8	1.21	CB3	32.6	1.59
CT4	4.6	0.23	CM4	22.1	1.08	CB4	32.0	1.56
CT5	5.6	0.28	CM5	22.6	1.10	CB5	32.6	1.59
CT6	4.6	0.23	CM6	22.1	1.08	CB6	32.6	1.59
Mean	4.9	$0.25 \pm .03$	Mean	23.4	$1.14 \pm .06$	Mean	33.0	$1.61 \pm .04$
$T_s = 86$ $P_s = 29.47 \text{ in-Hg}$ $M_s = 28.54 \text{ lb}_m/\text{lb mole}$ $U_{\text{Average}} = 20.4 \text{ ft/s}$ $\left(\frac{U_{\text{Local}}}{U_{\text{Average}}} \right)_{\text{Average}} = 1.00 \pm 0.58$								

TABLE 8: Velocity Traverses With Flow Straighteners Under Compliance Conditions

Test	Filter Drum	Dry Bulb Temperature °F	Wet Bulb Temperature °F	Moisture by Volume B _{Wo}	Volumetric Flow Rate ACFM	Emission Rate Based on Average Particulate Concentration lb _m /hr	Average Emission Rate During Compliance Testing ER _p lb _m /hr
1 Wind Speed: 8-12 mph Wind Direction: W Ambient Temp: 39°F Ambient Air: 0.0045 Moisture	A	88.5	86.0	0.041	10700	0.279	
	B	86.0	83.5	0.038	11100	0.289	
	C	85.0	83.0	0.038	11000	0.287	
	Totals or Averages	Moisture Condensation Method 0.036		0.039	32800	0.855	
2 Wind Speed: 8-12 mph Wind Direction: W Ambient Temp: 39°F Ambient Air: 0.0045 Moisture	D	86.0	83.5	0.038	11500	0.313	
	E	90.0	89.0	0.046	11300	0.308	
	F	93.0	88.5	0.044	11800	0.321	
	Totals or Averages	Moisture Condensation Method 0.040		0.043	34600	0.942	1.80
3 Wind Speed: 10-15 mph Wind Direction: S-W Ambient Temp: 44°F Ambient Air: 0.0037 Moisture	A	86.0	83.0	0.038	10100	0.250	
	B	86.0	85.0	0.041	10700	0.265	
	C	90.0	88.0	0.044	11300	0.280	
	Totals or Averages	Moisture Condensation Method 0.034		0.041	32100	0.795	
4 Wind Speed: 10-15 mph Wind Direction: S-W Ambient Temp: 44 Ambient Air: 0.0037 Moisture	D	88.0	87.0	0.044	11100	0.346	
	E	95.5	89.0	0.044	11700	0.365	
	F	97.0	89.0	0.044	10700	0.334	
	Totals or Averages	Moisture Condensation Method 0.056		0.044	33500	1.045	1.84
5 Wind Speed: 8-12 mph Wind Direction: W Ambient Temp: 45 Ambient Air: 0.0048 Moisture	A	91.0	90.3	0.048	10800	0.376	
	B	94.9	93.1	0.052	11100	0.387	
	C	99.3	94.0	0.052	9600	0.334	
	Totals or Averages	Moisture Condensation Method 0.045		0.051	31500	1.097	
6 Wind Speed: 8-12 mph Wind Direction: W Ambient Temp: 45 Ambient Air: 0.0048 Moisture	D	93.5	92.7	0.052	9000	0.211	
	E	96.3	93.1	0.051	10100	0.237	
	F	97.5	93.0	0.050	10000	0.235	
	Totals or Averages	Moisture Condensation Method 0.059		0.051	29100	0.683	1.78

TABLE 9. Compliance Testing Results

C. Evaluation of Dryer Efficiency

Table 10 illustrates the total energy consumption rates during each of the 3 compliance tests. These results are based on an average natural gas heating value of 1000 Btu/ft³ at 14.65 psia and 60°F. Personnel from Union Gas Limited confirmed that this was a representative figure for the Newbury, Ontario region [11, 12].

Corn drying parameters are summarized in Table 11. The initial and final moisture contents represent average values obtained from on-site determinations by St. Clair Grain and Feeds personnel and data supplied by Agriculture Canada, Canadian Grain Commission Inspection Division for random samples submitted by St. Clair Grain and Feeds.

Overall energy efficiencies, OE, are listed in Table 12.

Table 13 summarizes the thermodynamic drying efficiencies, DE, for the 3 compliance tests. The drying efficiency, DE, represents the ratio of the actual rate of water removal from the corn to the maximum attainable if the air left the dryer at saturation conditions (i.e. 100% relative humidity).

D. Behlen "Rotovac" System Performance

The particulate collection capabilities of the Behlen "Rotovac" system are illustrated in Table 14.

Test No.	Gas Consumption		Fuel Energy Btu/hr	Fuel Energy Cost* ¢/bushel of dry corn	$H_P \times 42.418 \times 60 = \frac{\text{Btu}}{\text{hr}}$		Total Energy Btu/hr
	ft ³ /hr at 14.65 psia 60°F	ft ³ per bushel of dry corn			Total Electric Demand		
					(kw)	Btu/hr	
1	13,470	18.49	13,470,000	4.8	136.3	465,000	13,940,000
2	14,376	20.83	14,376,000	5.4	136.3	465,000	14,840,000
3	12,745	18.70	12,745,000	4.9	136.3	465,000	13,210,000
4	12,943	20.15	12,943,000	5.2	136.3	465,000	13,410,000
5	13,372	21.40	13,372,000	5.6	136.3	465,000	13,840,000
6	15,091	20.53	15,091,000	5.3	136.3	465,000	15,560,000
Average		20.02		5.2			

*based on a natural gas cost of \$2.60 per thousand cubic feet

TABLE 10: Summary of Total Energy Consumption for Drying Shelled Corn During Compliance Testing

Test No.	Discharge Test Weight of Dried Corn lb _m /bu	Weight of Water Removed From Corn lb _m /hr	Initial Moisture Content % by Weight	Final Moisture Content % by Weight	Volumetric Flow Rate of Dried Corn bu/hr
1	55.54	6378	26.4+1.2	14.8+1.2	728.6
2	55.54	6344	26.9+1.4	14.8+1.2	690.1
3	54.77	6612	26.6+1.1	13.6+1.2	681.6
4	55.87	6624	28.5+1.8	15.3+0.5	642.2
5	55.93	6520	28.7+0.9	15.4+1.6	625.0
6	55.61	8050	28.9+1.2	14.9+0.6	735.2

TABLE 11: Corn Drying Parameters During Compliance Testing

Test	Total Energy Consumption, E Btu/hr	Moisture Removal Weight, W lb _m /hr	Total Energy Consumption Per lb _m of Moisture Removed Btu/lb _m	Energy Efficiency $\frac{W \cdot \lambda}{E} \times 100$
1	13,940,000	6378	2,186	59.5
2	14,840,000	6344	2,339	55.6
3	13,210,000	6612	1,998	65.1
4	13,410,000	6624	2,024	64.2
5	13,840,000	6520	2,123	61.2
6	15,560,000	8050	1,933	67.3
$\lambda = 1300 \text{ Btu/lb}_m \text{ water [13]}$				

TABLE 12: Overall Energy Efficiencies

Test	Average Water Removal Rate From Corn $W(\text{lb}_m/\text{hr})$	Ambient Air Absolute Humidity $\frac{\text{lb}_m \text{H}_2\text{O}}{\text{lb}_m \text{dry air}}$	Drying Air Mass Flow-Rate $\frac{\text{lb}_m \text{dry air}}{\text{hr}}$	Water Production Rate by Combustion $\frac{\text{lb}_m \text{H}_2\text{O}}{\text{hr}}$	Water Supplied With Ambient Air $\frac{\text{lb}_m \text{H}_2\text{O}}{\text{hr}}$	Absolute Humidity of Inlet Drying Air, H_i $\frac{\text{lb}_m \text{H}_2\text{O}}{\text{lb}_m \text{dry air}}$	Absolute Humidity of Drying Air at Saturation, H_s $\frac{\text{lb}_m \text{H}_2\text{O}}{\text{lb}_m \text{dry air}}$	Drying Efficiency %
1&2	6361	0.0028	313,321	1314	877	0.00699	0.0368	60
3&4	6618	0.0023	309,944	1212	713	0.00621	0.0407	62
5&6	7285	0.0030	279,060	1343	837	0.00781	0.0473	66

TABLE 13: Thermodynamic Drying Efficiencies

Test	Total Rotovac Emission Rate lb _m /hr	Cyclone Catch Rate lb _m /hr
1 & 2	1.8	22
3 & 4	1.8	47.1
5 & 6	1.8	99.2

TABLE 14 : Performance Characteristics of Behlen "Rotovac"
Particulate Collection System

Particle size distributions of the solid emissions from the exhaust louvres are provided by Table 15. The remainder of the sample (74.4, 59.1 and 94.2% for Tests 1, 2 and 3 respectively) was captured in the nozzle and front end of the Andersen impactor which was arranged as illustrated in Figure 16.

The moisture levels of the gases leaving the exhaust louvres are compared to saturation conditions in Table 16.

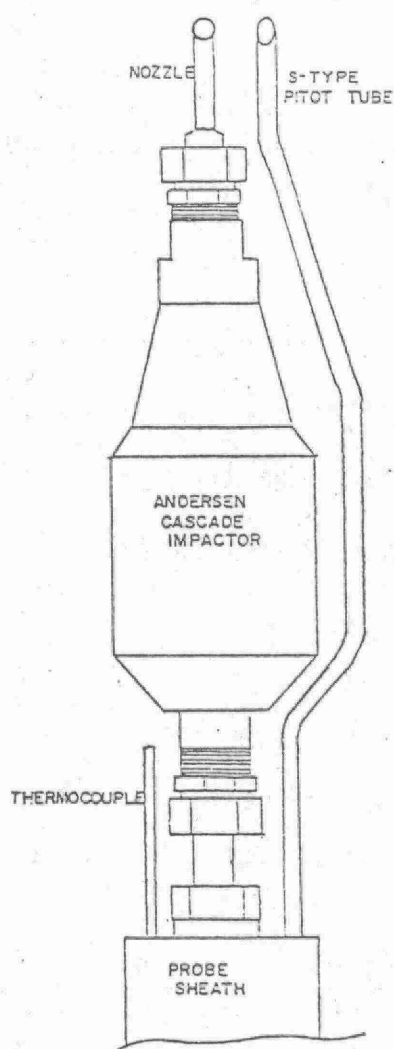


FIGURE 16: Arrangement of Extended S-Type Pitot Tube With Respect to Andersen Cascade Impactor and Sampling Nozzle

Andersen Test 1		Andersen Test 2		Andersen Test 3	
D_p (μ)	% < D_p on Mass Basis	D_p (μ)	% < D_p on Mass Basis	D_p (μ)	% < D_p on Mass Basis
11.0	25.6	9.1	40.9	9.4	5.8
6.9	12	5.8	22.7	5.9	
4.6	8	3.9	4.5	4	
3.2	3.2	2.7		2.8	
2.0	0.8	1.7		1.7	
1.0		0.85		0.9	
0.6		0.52		0.54	
0.4		0.34		0.36	

TABLE 15: Particle Size Distributions on a Mass Basis of Particulate Emissions from Behlen "Rotovac" Control System

Test	Filter Drum	Dry Bulb Temperature °F	Wet Bulb Temperature °F	Absolute Humidity	Saturation Humidity	% Relative Humidity
				lb _m H ₂ O/lb _m dry air		
1	A	88.5	86.0	0.0266	0.0297	89.6
	B	86.0	83.5	0.0246	0.0273	90.1
	C	85.0	83.0	0.0246	0.0264	93.2
Absolute Humidity by Condensation Method: 0.0233				0.0253	0.0278	91.0
2	D	86.0	83.5	0.0246	0.0273	90.1
	E	90.0	89.0	0.0300	0.0312	96.2
	F	93.0	88.5	0.0287	0.0344	83.4
Absolute Humidity by Condensation Method: 0.0260				0.0278	0.0310	89.9
3	A	86.0	83.0	0.0246	0.0273	90.1
	B	86.0	85.0	0.0266	0.0273	97.4
	C	90.0	88.0	0.0287	0.0312	92.0
Absolute Humidity by Condensation Method: 0.0219				0.0266	0.0286	93.2
4	D	88.0	87.0	0.0287	0.0292	98.3
	E	95.5	89.0	0.0287	0.0373	76.9
	F	97.0	89.0	0.0287	0.0391	73.4
Absolute Humidity by Condensation Method: 0.0369				0.0287	0.0352	82.9
5	A	91.0	90.3	0.0314	0.0322	97.5
	B	94.9	93.1	0.0342	0.0366	93.4
	C	99.3	94.0	0.0342	0.0422	81.0
Absolute Humidity by Condensation Method: 0.0293				0.0333	0.0370	90.6
6	D	93.5	92.7	0.0342	0.0349	98.0
	E	96.3	93.1	0.0335	0.0345	97.1
	F	97.5	93.0	0.0328	0.0398	82.4
Absolute Humidity by Condensation Method: 0.0391				0.0335	0.0364	92.5

TABLE 16: Moisture Levels of Exhaust Gases in the Sampling
Duct Extensions

VI. DISCUSSION OF RESULTS

A. Preliminary Survey Testing

An examination of Tables 5, 6, 7 and 8 indicates that there were significant velocity differences in the vertical direction in the sampling duct extensions as recorded at the T, M and B elevations. Without flow straighteners there were points in the top sections, T, of the extensions where zero or negative velocity readings were obtained. Use of the egg-crate flow straighteners eliminated the dead space and reversed flow regions. The improvement in the velocity profiles at each elevation of sampling duct C is shown in Tables 7 and 8 in terms of the comparison between the standard deviations from the mean values of $U_{\text{Local}}/U_{\text{average}}$ at the T, M and B levels. The use of the egg-crate flow straighteners produced essentially uniform velocity profiles at each elevation, which facilitated representative sample collection.

B. Compliance Testing

Table 9 illustrates the performance of an "environmentally clean" grain drying operation. The particulate emission rate of $1.81 \pm 0.03 \text{ lb}_m/\text{hr}$ corresponds to the effluent from the dryer itself, based on 3 complete particulate loading determinations. The emission rate from the overall operation would not be expected to exceed this level to any significant extent. Although the exhausts from the high efficiency cyclones

collecting particulate matter from the "Rotovac" filter surfaces were not sampled, visual observations suggested negligible particulate loadings in these exit streams. Several independent confirmations of low particulate emissions from the high efficiency cyclones were provided by participants at the Technical Committee of the Ontario Grain and Feed Dealers meeting held at the University of Windsor on 8 February 1980 [14, 15].

The sampling strategy had been designed to provide particulate emission rate data for each side of the dryer. Since there was no consistent pattern to the differences in

- i. particulate emission rates
- ii. temperatures
- iii. humidities

found at the two sides of the dryer it would appear that the drying operation had not been unbalanced by the sampling modifications.

The relatively good agreement between effluent gas humidities obtained from the condensation technique, which provided integrated samples over 45 minute periods, and the wet and dry bulb temperatures, which were obtained over 3 to 5 minute measuring intervals, suggests that the grain dryer operated at essentially a constant moisture removal rate during each test.

1. Emission Factors

The results of this testing program provide emission factors that will be useful for future design and compliance purposes. Table 17 shows that for the "ACE" Model 2165-D dryer

Test	Dryer Emission Rate lb_m/hr	Emission Rate Per 1000 bu Dried Corn $\text{lb}_m/1000 \text{ bu}$	Emission Rate Per 1000 lb_m of Water Removed $\text{lb}_m/1000 \text{ lb}_m \text{ H}_2\text{O}$
1 & 2	1.797	2.54	0.282
3 & 4	1.840	2.80	0.278
5 & 6	1.780	2.69	0.253
Mean	1.81 ± 0.03	2.68 ± 0.13	0.271 ± 0.016

TABLE 17: Emission Factors for "ACE" Model 2165-D Dryer Equipped
With Behlen "Rotovac" Control System

equipped with a Behlen "Rotovac" exhaust air cleaning system, particulate emission rates from the exhaust louvres, based on $(\text{lb}_m \text{ particulate})/(\text{1000 bu of dried corn})$ and $(\text{lb}_m \text{ particulate})/(\text{1000 lb}_m \text{ H}_2\text{O removed})$ are 2.68 ± 0.13 and $0.271 \pm .016$ respectively.

2. Comparison of Design and Actual Dryer Characteristics

During the testing program the "ACE" Model 2165-D dryer operated at an average throughput of 684 bu/hr. This represents 68.4% of design capacity based on #2 corn at 15% moisture removal. Although the testing period was designed to coincide with the peak of the drying season inclement weather conditions hampered grain deliveries to the drying facility. Consequently, there were intervals when the dryer was operated below rated capacity during each compliance test.

Dryer capacity tests, carried out by St. Clair Grain and Feeds personnel, after the compliance sampling program, showed that throughputs exceeding 1150 bu/hr could be attained with feed corn containing 24% to 26% moisture [16].

The volumetric flow rates measured during each compliance test ranged from 63,000 to 70,000 scfm. assuming negligible leakage through the dryer housing and blanked exhaust louvres, but including the gas volumes required for cleaning the filter screens. According to the fan curves supplied by Dorssers Welding Company Limited [17] a volumetric flow rate of 174,720 scfm at 70°F and 2 in. W.P. is expected. Since the actual flow was less

than 50% of the design value it would appear from an examination of the fan curves that the total pressure drop experienced by the fan was of the order of 6 to 7 in. W.P. Dorssers [18] reported that static pressures measured at the fan discharge varied from $2\frac{1}{2}$ to $2\frac{5}{8}$ in W.P. This range of values suggests that the resistance to flow at the suction side of the fan could be equivalent to 4 in. W.P. Such a possibility was confirmed by Dorssers [18].

Apparently, the area originally provided for ambient air flow directly into the fan was insufficient. Consequently, during the compliance sampling program much more than the design volume of ambient air was drawn through the cooling section of the dryer. The pressure drop through the intake louvres and grain column in the cooling section would have been sufficient to reduce the performance capabilities of the fan below the fan curve ratings. Experimental data show that even relatively minor modifications to fan inlet configurations can create significant losses in volumetric capacities [19].

The high flow rates through the cooling section were likely responsible for the accumulation of solids observed at the screens of the cooling section during the compliance sampling program. According to Archibald [15] this was the first time that screens in the dryer cooling section had to be cleaned during the drying season.

C. Evaluation of Dryer Efficiency

Dryer efficiencies can be evaluated in several different ways depending on the viewpoint to the emphasized. According to Otten [13] there are three drying efficiencies that are encountered in the grain drying business.

1. Fuel or Thermal Efficiency [13]

The fuel or thermal efficiency is used primarily for advertising purposes because it provides higher values by neglecting the electrical energy used to drive fans, metering rolls and any associated pollution control equipment. Fuel or thermal efficiencies are calculated from the relationship

$$TE = \frac{W\lambda}{E_{\text{fuel}}} \times 100\% \quad (1)$$

using high ambient temperatures and high initial grain moisture contents.

where

TE = fuel or thermal efficiency

W = average rate of water removal, $\text{lb}_m \text{H}_2\text{O/hr}$

λ = average latent heat of vaporization of water, Btu/lb_m

E_{fuel} = fuel energy consumption rate, Btu/hr

Because the data in Table 10 show that the total electrical energy requirements never exceeded 3.5% of the total energy consumption, the fuel or thermal efficiencies would not be significantly higher than the overall energy efficiencies which are based on total energy utilization.

2. Overall Energy Efficiency [13]

The grain dryer operator is interested in the overall performance of a unit in terms of the overall energy efficiency defined by the expression

$$OE = \frac{W\lambda}{E_{\text{total}}} \times 100\% \quad (2)$$

where

OE = overall energy efficiency

W = average rate of water removal, $\text{lb}_m \text{H}_2\text{O/hr}$

λ = average latent heat of vaporization of water, Btu/lb_m

E_{total} = total energy consumption rate, Btu/hr

The average rate of water removal, W, is evaluated from

$$W = (\text{BU})(\text{TW}) \left[\frac{x_i - x_f}{100 - x_i} \right] \quad (3)$$

assuming that dry matter loss during drying is negligible, where

BU = volumetric flow rate of dried grain, bu/hr

TW = discharge test weight of dried grain, lb_m/bu

x_i = initial grain moisture content, % by weight

x_f = final grain moisture content, % by weight

The "ACE" Model 2165-D dryer is essentially a cross-flow unit. Consequently, there will be significant temperature

variations from top to bottom and from the warm air plenum side to the exhaust air housing side of each grain column. Because it would be extremely difficult to determine values of the latent heat of vaporization of water corresponding to different positions in a grain column it is reasonable to use an average value. Previous investigators [13, 20] have assumed $\lambda = 1300 \text{ (Btu)/(lb}_m \text{H}_2\text{O evaporated)}$ as a representative value for the overall vaporization process.

An examination of Table 10 shows that the total electrical energy demand varied from 3.0% to 3.5% of the total energy utilization. On this basis it is apparent that electrical energy requirements represent a minimal fraction of corn drying costs. The gas consumption per bushel of dried corn averaged 20.02 ft^3 which translated into a drying cost of 5.2¢/bushel based on a natural gas cost of $\$2.60/1000 \text{ ft}^3$.

The data in Table 12 show that the total energy needed to remove 1 lb_m of water from the corn varied from 1,933 to 2,339 Btu. Overall energy efficiencies with no drying air recycling ranged from 55.6 to 67.3%.

In practice, the overall dryer efficiency is expected to depend on

- i. the inlet grain temperature
- ii. the ambient air temperature
- iii. the moisture content of the inlet grain
- iv. the moisture content of the dried grain
- v. the recirculation rate of drying air
- vi. the ratio of cooling air flow, which passes through the grain column from the cooling air plenum, to that fed directly to the fan

- vii. the drying air temperature in the warm air plenum
- viii. the amount of insulation provided on the dryer walls
- ix. the frequencies and durations of dryer shutdowns due to equipment failure, dryer maintenance, etc.
- x. the availability of grain during the drying period.

During this study, parameters v, vi, vii and viii were essentially constant during each test. Lower ambient air and corn temperatures can be correlated to decreased overall drying efficiencies, however, the available data are insufficient to provide definite conclusions with respect to these variables and the initial and final corn moisture levels.

3. Thermodynamic Drying Efficiency [13]

Drying can be achieved at any location in the grain columns as long as the air passing through the material being dried is not saturated with water vapor at the column temperature. For maximum profit, dryers should be designed to provide optimal air-grain contact so that the drying air attains essentially 100% relative humidity locally.

By definition, the thermodynamic drying efficiency represents the ratio of the actual rate of water removal to the maximum drying rate attainable if the air left the dryer in a saturated state at the operating conditions. Mathematically it is expressed by

$$DE = \frac{W}{A(H_s - H_i)} \times 100\% \quad (4)$$

where

DE = thermodynamic drying efficiency

W = average rate of water removal, $\text{lb}_m \text{H}_2\text{O}/\text{hr}$

A = average mass flow rate of drying air, $\text{lb}_m \text{ dry air}/\text{hr}$

H_i = absolute humidity of inlet drying air, $\text{lb}_m \text{H}_2\text{O}/\text{lb}_m \text{ dry air}$

H_s = absolute humidity of drying air at saturation ,
 $\text{lb}_m \text{H}_2\text{O}/\text{lb}_m \text{ dry air}.$

The absolute humidity of the inlet drying air, H_i , is determined from the absolute humidity of the ambient air and the amount of water produced by the combustion of the natural gas. The composition of the natural gas supplied to the Newbury, Ontario region is tabulated in Appendix III.

It is not as easy to provide a precise value for H_s , the absolute humidity of the drying air at saturation, for the dryer under investigation because the magnitude will depend on the temperature used to define saturation conditions. Although temperatures were measured on the exhaust side of one grain column at 10, 30 and 50 foot distances from the top of the column, it is difficult to estimate an appropriate temperature for calculation purposes.

The locations of the "Rotovac" filter modules create such complex gas flow patterns inside the dryer exhaust housing that the prediction of a representative temperature would be very difficult without extensive experimental measurement of dryer temperatures in the exhaust housing. Consequently, the

drying efficiencies, DE, have been evaluated for saturation conditions determined by the average temperatures recorded by the sensor located 30 feet from the top of the column. This location appears to best approximate the temperature of the gases entering the exhaust housing from the grain column.

Table 13 lists the thermodynamic drying efficiencies for the 3 compliance tests on the basis of negligible gas leakage through the blanked exhaust louvres of the "Rotovac" air filters, but including the gas volumes passed through the high efficiency cyclones.

D. Behlen "Rotovac" System Performance

Table 14 can be used to evaluate the particulate collection efficiency of the Behlen "Rotovac" control system if it is assumed that the high efficiency cyclones associated with the filter screens operate at essentially 100% efficiency.

The cyclone catch rate was determined by weighing the collected solids at the end of each compliance test. This was accomplished by emptying the cyclone bin into a dump truck which was located below in the wet grain receiving area. During windy periods this transfer process could lead to excessive losses of solids if the doors to the receiving area were not closed. Such undesirable conditions were experienced at the end of the first 2 compliance tests (tests 1 and 2 and tests 3 and 4). Minimal losses occurred at the end of the last compliance test (tests 5 and 6) when the transfer from the cyclone bins to the truck was conducted with the doors to the receiving area closed.

An examination of Table 14 shows that without the Behlen "Rotovac" system, uncontrolled emissions from the dryer would be about $101 \text{ lb}_m/\text{hr}$ or $148 \text{ lb}_m/1000 \text{ bu}$ of dried corn. It would appear that the particulate collection efficiency of the "Rotovac" system is of the order of 98%.

Table 15 summarizes the three particle size distributions on a mass basis obtained with an Andersen "in-stack" inertial cascade impactor type of classifier. It is important to recognize that there were virtually no solid particles in the submicron range emitted from the exhaust louvres. Approximately 60% of the particulate matter exceeded a 10 micron diameter. This size distribution was confirmed by the relative amounts of material collected in the various components of the stack sampling train. About 99% of the samples were found in the nozzle, probe and cyclone. Insignificant weights were detected on the filter and virtually nothing reached the impingers.

The preponderance of large particles, corresponding to whole and parts of beeswings, in the emissions from the exhaust louvres suggests leakage through the seals around the "Rotovac" filter drums. According to Chapman [21] the seals had to be adjusted during the compliance sampling program.

An examination of Table 16 shows that on the basis of wet and dry bulb temperature measurements the gases leaving the Behlen "Rotovac" modules are not saturated (i.e. relative humidity is less than 100%) with water vapor. This means that there

VII. CONCLUSIONS AND RECOMMENDATIONS

The results of this investigation show that the installation of Behlen "Rotovac" particulate control equipment on an Ace 2165-D grain dryer reduced particulate emissions to the atmosphere to approximately 3 lb_m particulate per 1000 bu of dried corn.

The overall energy efficiencies, OE, and thermodynamic drying efficiencies, DE, ranged from 56 to 67% for no recirculation of air from the exhaust housing to the fan inlet. Since this study showed that more than 95% of grain dryer energy costs are due to fuel consumption and more than 15 million dollars are spent annually in Ontario by the grain drying industry for heating fuels it is recommended that a more comprehensive energy utilization study be conducted.

The operation of a typical grain dryer can be modelled from basic principles to provide a means of improving the design and operating conditions for optimization of energy efficiency. Since this study was primarily concerned with the evaluation of particulate emission rates insufficient temperature and pressure drop instrumentation were available for model validation. The recommended energy utilization study should include the determination of the effect of

- i. the inlet and outlet grain temperatures
- ii. the ambient air temperature
- iii. the moisture contents of the inlet and dried grains

- iv. the recirculation rate of drying air
- v. the ratio of cooling air flow, which passes through the grain column from the cooling air plenum, to that fed directly to the fan
- vi. the drying air temperature in the warm air plenum
- vii. the moisture content of inlet, recirculated and exit air streams
- viii. the amount and location of insulation provided on the dryer walls
- ix. the effect of added particulate control equipment on dryer energy performance.

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